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U. S. WATER CONSERVATION LABORATORY
U. S. Department of Agriculture
Agricultural Research Service
Western Region
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Phoenix, Arizona 85040

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Allen, Stephen G.	Plant Physiologist
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Pendrick, Annette M.	Biological Aide
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TITLE: GERMPLASM DEVELOPMENT AND DOMESTICATION OF CUPHEA AND OTHER NEW CROP SPECIES

NRP: 20160 CRIS WORK UNIT: 5422-20160-004-00

INTRODUCTION

Numerous studies have identified the need and potential of new or alternate crops research. High yields of traditional crops in the arid Southwest depend upon extensive irrigation. New crops with low water use will be needed if agriculture is to persist in the region.

The U. S. chemical industry is heavily dependent upon imported coconut and palm kernel oils as the primary source of lauric acid for manufacturing soaps, detergents, lubricants, and other related products. Seed oils from species of *Cuphea* contain high levels of lauric and other medium-chain fatty acids. Seed dormancy, seed shattering, sticky glandular hairs, and indeterminate patterns of growth and flowering are major constraints to domestication.

The U. S. is also completely dependent upon imported castor oil for its total supply of hydroxylated fatty acid, a strategic material used for the production of lubricants, plasticizers, protective coatings, surfactants, and pharmaceuticals. High seed toxicity and allergenic reactions from plants limit production of castor beans in the U. S. Seed oils from species of *Lesquerella*, many of which are adapted to arid lands, contain sizable quantities of 3 hydroxy fatty acids. Domestication of adapted species appears feasible.

PROCEDURE

This project has responsibility for assembling, multiplying and maintaining a working germplasm collection of the various species of cuphea and lesquerella. The project provides overall liaison and coordination of the USDA/ARS cooperative cuphea program with state agricultural experiment stations and industry, and provides significant financial resources for cooperative research: (1) Participates in an equal, three-way funding (USDA/ARS, Oregon State AES, and member companies of the Soap and Detergent Assoc.) of research in Oregon under a specific cooperative agreement (58-9AHZ-3-744). Results of this research are presented in a separate report (CRIS No. 5422-20160-004-01). (2) Supports research by broadform cooperative agreements on interspecific hybridization and cytogenetics of cuphea at the Arizona AES (58-9AHZ-3-38), and development of cuphea tissue culture technology at the Purdue AES (12-14-3001-259).

Germplasm receives thorough evaluation with special attention for potential adaptation to arid conditions. Agronomically promising species are selected, and breeding and genetic techniques employed to develop useful, enhanced germplasm and breeding lines. Both intra- and interspecific crossing are utilized to obtain new genetic recombinations leading to removal of constraints to domestication and productivity.

RESULTS AND DISCUSSION

Fifty freshly harvested seeds from each of 589 second-selection cycle, rapidly-germinating progeny of 3 species--*Cuphea wrightii* (556), *C. tolucana* (29), and *C. paucipetala* (4) were germinated in the greenhouse. In total, 29,105 seeds were planted. Dormancy was not overcome by selection since emergence of only 36 seedlings from 17 selections were observed up to 75 days after planting (Table 1). Seed was harvested from 13 surviving seedlings for further testing. Remnant seed of the 589 single plant selections plus selfed seed from 96 plants of 5 additional accessions of *C. wrightii* and 168 plants of 2 accessions of *C. lutea* are now available for oil and fatty acid analysis to determine extent of genetic variability for this important character.

The compact growth habit found in 2 accessions of *C. leptopoda* was characterized (Table 2). Reduced plant height (34 cm for normal vs 22 cm for compact at 65 days after planting) is chiefly caused by shortened internode length, which is most pronounced in the 3rd to 7th internodes. Inheritance of the character appears to be conditioned by a single recessive gene, but confirmation from crosses and progeny tests is being delayed by seed dormancy.

Eleven interspecific *Cuphea* hybrids involving 7 species (*C. crassiflora*, *C. laminuligera*, *C. lanceolata*, *C. leptopoda*, *C. lophostoma*, *C. llavea*, and *C. procumbens*) have been successfully made and verified cytologically. Reciprocal cross combinations involving an annual species, *C. procumbens* (n=9) with the perennial species *C. llavea* (n=9) have resulted in relatively fertile F_1's with normal diploid chromosome pairing and viable seed production. Backcross populations are being developed. F_2 populations will be grown out and evaluated for unique, transgressive segregation as soon as seed dormancy is overcome. Another unique combination is the F_1 hybrid of *C. leptopoda* (n=10, capric acid-C_{10}) x *C. laminuligera* (n=10, lauric acid-C_{12}). This is the first interspecific hybrid between a species with lauric acid and one with capric acid as the predominant fatty acid in the seed oil. This hybrid flowers profusely, but appears to be sterile and has not yet set seed by selfing or backcrossing. Research is in progress to develop methods for using colchicine to double chromosome numbers of hybrids to restore fertility and produce amphidiploids.

One accession of *C. wrightii* was grown for a second year at 10 locations throughout the country. Performance was variable at the different locations (Table 3). Rainfall hampered harvest at Ames, IA and Experiment, GA. Excessive weeds forced abandonment of plots at Lafayette, IN. Again, seed set was severely limited at Phoenix due to high temperatures. Reasonably good seed production was observed at Medford, OR, Jacksonville, IL, and Isabela, PR. Limited evaluation of *C. laminuligera* and *C. lutea* was made at 3 locations in Oregon and at Phoenix (Table 4). Seed of these 2 species plus additional accessions of *C. wrightii* are being increased for wider testing in 1986.

Plans were made to transfer the USDA/ARS cuphea germplasm collection to the North Central Plant Introduction Center at Ames, IA, to provide better facilities for maintenance, increase, and distribution. In addition, 2 SY's are being added to extend and strengthen the program of germplasm evaluation and testing for adaptation in the Midwest and Southeast. The status and distribution of the cuphea germplasm collection is summarized in Table 5.

Seed viability and germination percentages were determined on the lesquerella germplasm collection. Some germination was obtained from over 92% of the accessions received. Most of the seed had been collected between 1960 and 1970, and seed lots had been last grown for observation and increase during the period of 1966 to 1972. Large differences were observed both between species and among accessions within species. Variation in seed germination was expected, and under the circumstances the retention of viability was considered good. Seed dormancy, which can be a problem with newly harvested seed of some species of lesquerella, was judged not to be a problem in this instance.

Field survival of over 2,100 transplanted and 5,900 direct seeded plants was only 8% (Table 6). A period of 90 days elapsed from the time the seeds were planted in the greenhouse for determination of germination and the time the seedling plants were transplanted into the field. A mean survival rate of 65% was experienced for all species during the time the plants were grown in small pots in the greenhouse. For comparison, the species are grouped as to geographic origin and type of hydroxy fatty acid produced in the seed oils. The range in survival among species was 13 to 96%. It is significant to note that only 52% of the L. fendleri and 19% of L. gordonii plants, which are both native to arid areas of Arizona, New Mexico, and Texas, survived this period of time. As a whole, the five densipolic acid producing species native to the humid, temperate conditions of Tennessee and adjacent areas exhibited a high survival rate (90%) during this same period of time.

Within 25 days after transplanting (DATP) the survival rate of all transplanted plants had dropped to 51% (Table 6). Overall, the survival rate of the densipolic acid producing species declined to 61%. After 50 DATP the survival rate was 31%, and no plants survived 150 DATP. Some of the plants had flowered, but none produced seeds. The exact reason for this attrition is not known. However, it is reasonable to believe that lack of adaptation to relatively high soil salinity and pH is a major factor.

Species within the lesquerolic acid group, which are largely native to an area from Arizona to Texas and Oklahoma, exhibited a rather high mean rate of attrition before transplanting (39% vs 10% for the densipolic group). However, the survival of plants after transplanting was generally higher for the lesquerolic group (Table 6). At 50 DATP, 43% of the original seedlings and 71% of the transplanted plants of the lesquerolic group had survived compared to 31% and 35%, respectively, for the densipolic group.

The initial attrition of plants of L. fendleri was 48%, but at the end of 200 DATP 21% of the original seedlings and 40% of the transplanted plants were viable. Most surviving plants produced a good yield of seed. The attrition rate of L. gordonii, which is native to south central Arizona, was excessively high with only 19% of the seedling plants surviving at the time of transplanting. Most of the plants that survived to 150 DATP had flowered, but relatively few produced any seed. The only other species that produced any quantity of seed were L. pinetorum and L. purpurea. These two species appear to be adapted to arid conditions, but neither have plant characteristics that would make them good candidates for domestication in their present form. However, they do have larger seed size, and may provide other desirable genetic characteristics through interspecific hybridization.

The performance of seedling plants by direct seeding in the field was generally comparable to those in the transplanted plots (Table 6). Again, large variation in germination rate and seedling emergence, and ultimate survival of the plants was observed among the species tested. L. fendleri appeared to be the best adapted, even though the ultimate survival rate was only 16%. Survival rates varied considerably among the 24 accessions of L. fendleri, ranging from 0 to 75%. Initial survival of direct seeded L. gordonii was superior to L. fendleri, but plant stand of this species dropped to only 8% and 1% at 150 and 200 DAP, respectively. Very few seeds were harvested from the few surviving L. gordonii plants, and essentially no seed was produced by any other species except L. fendleri. Most of the surviving plants of L. fendleri grew vigorously, flowered, and produced a good yield of seed.

A series of 56 single plant selections were made within the transplanted and direct seeded plantings. Of this total, 46 were from 16 accessions of L. fendleri. A total of 28 were from the direct seeded and 18 from the transplanted plots. Only 6 selections were made from 5 accessions of L. gordonii, and one selection each from L. gracilis, L. grandiflora, L. palmeri, and L. purpurea. Seed set on the 10 selections of these 5 species was very limited.

Plant measurements of 15 selections of L. fendleri with the highest seed yield from the direct seeded planting are summarized and presented in ranked order (Table 7). Seed yields of individual plants ranged from 6.4 to 19.7 grams, thus bracketing the yield of the wild plant observed by Gentry and Barclay (1962). The rather large ranges in variability of seed weight, dry weight of plants, and the related measurement of harvest index suggest that adequate genetic variability is present within the species and should be amenable to selection. Relatively less variation appears to be present for 1,000 seed weight and plant height.

Estimated yields of biomass, seed, seed oils, lesquerolic acid, and seed proteins were based upon a conservative plant population of 150,000 plants/ha. The average figures for L. fendleri of 25% seed oil of which 60% is hydroxy fatty acid (lesquerolic acid), and 23% seed protein were used to complete the estimations (Table 7). The data show a wide range

in seed yield from 960 to 2,955 with a mean of 1,564 kg/ha. Over two-thirds of the selections equal or exceed the yield estimate of 1,120 kg/ha made by Gentry and Barclay (1962). These are judged to be respectable yields for an oilseed plant that has received little attention from breeding and selection.

Linear correlations were calculated among the five yield and plant measurements (Table 8). In general, little relationship was detected among these parameters. Seed yield and plant dry weight were positively correlated at the 5% level of probability. This relationship may prove useful in selection for increased seed yield, but only approximately one-third of the variability in seed yield is accounted for by this correlation. No apparent relationship was detected between seed yield and harvest index. However, harvest index was negatively correlated with dry weight of plant at the 1% level of probability. This would indicate that selection for large plants may increase seed yield per plant within limits, but the amount of seed produced on a plant relative to the biomass would be reduced. At this time it is too early to predict the interactive effects of plant population, water management, and other cultural factors on the various components of yield. More research is needed in this regard.

Calculations were made to provide some estimate of the potential economic value of lesquerella as a new industrial oil seed crop for the arid Southwest (Table 9). Since no actual production data are available for lesquerella, production costs for wheat in Arizona were used and modified slightly to provide an estimate. As currently visualized, lesquerella could be produced in a cropping system very similar to wheat or the other small grains as a winter crop. Seed yields of approximately 2,400 kg/ha would be needed to meet the total cost of production. Only 2 of the 15 selections listed in Table 7 exceeded the breakeven yield. If yields of 3,000 kg/ha were realized, which is essentially that obtained from the best selection, a return of approximately $120 per hectare could be realized.

Most lots of _L. fendleri_ seed harvested in May and June, 1985, germinated very well, thus indicating that seed dormancy is not likely to be a problem with this species. A one-half acre planting of the selections and bulk lots of _L. fendleri_ was made at the Maricopa Agricultural Center on October 8th. Germination was good and relatively good stands were obtained.

SUMMARY AND CONCLUSIONS

Simple selection for overcoming cuphea seed dormancy has not as yet proved to be effective. Some germination of fresh seeds of _C. wrightii_ has been effected by acid scarification, which may prove useful in a breeding program with limited quantities of seed. Additional research on seed physiology, was well as on breeding and selection, will be needed to alleviate this problem with _C. wrightii_ and other potentially useful species.

The generation of unique, potentially useful genetic variation through recombination following interspecific hybridization appears to be fully feasible. Certain combinations such as the cross between the morphologically divergent, herbaceous annual species C. procumbens and the semi-woody, perennial species C. llavea, which give rise to relatively fertile F_1's, hold promise for ready release for new genetic variability by recombination and segregation. The successful hybrid between a lauric acid (C. laminuligera) and a capric acid (C. leptopoda) producing species may provide basic information on the genetic control of fatty acid biosynthesis. In addition, these 2 species are among the 5 most promising species for domestication. Conceivably, it may be possible to isolate and select plant types with better agronomic adaptation from this cross. In addition, it may be possible to transfer the compact plant habit found in C. leptopoda into other genetic backgrounds.

The steps being taken to transfer the germplasm collection to Ames, IA and more fully integrate it into the national germplasm system are positive. The climatic limitations to field production of cuphea seed at this location was a severe constraint. However, over 40% of the accessions and 54% of the species in the collection were increased in Phoenix over the past 2 years. A full, working germplasm collection is being maintained at Phoenix and will serve as a backup for the collection at Ames, IA.

Continued effort will be made to characterize and determine the inheritance of the compact growth habit in C. leptopoda. Additional interspecific hybrid combinations will be attempted and continued effort will be expended on characterizing existing hybrids. F_2 and backcross populations of the various C. procumbens x C. llavea cross combinations will be grown out and analyzed for transgressive segregation. Oil and fatty acid analysis will be made on various parents, F_1's and progeny. Colchicine methodology will be developed and utilized to produce amphidiploids to restore fertility to sterile F_1's.

Limited funds necessitated termination, at the end of FY 85, of the broadform cooperative agreement with Purdue University to conduct cuphea tissue culture research. Continued funding of cooperative cytogenetic research on cuphea species and interspecific hybrids at the University of Arizona is highly essential and will be continued. This project will continue to provide funding and liaison with the cooperative research conducted at Oregon State University under the specific cooperative agreement in combination with equal funding from industry.

Various accessions of 7 cuphea species, which have been grown under different ecological conditions, are being prepared for oil and fatty acid analysis at the NRRC, Peoria, IL. Each lot has been divided on the basis of seed maturity to determine the effect of harvesting green or less mature seed on oil quantity and quality. Genetic variability for oil quantity and fatty acid distribution among single plant progeny of various accessions of C. wrightii and C. lutea will be assessed following chemical analysis.

Responsibility for regional adaptation testing of Cuphea species in 1986 will be assumed by Dr. W. W. Roath at Ames, IA. Dr. C. A. Jaworski will conduct research on adaptation of cuphea to the Southeastern part of the U. S.

Seed yields of single plant selections of *Lesquerella fendleri* indicate that the economic potential of this species is sufficiently high to justify increased breeding and agronomic research. As currently visualized, lesquerella could be produced in a cropping system very similar to wheat or other small grains as a winter crop in the arid Southwest. Relatively simple breeding and selection methods should significantly improve production by enhancing seed yield, oil percentage and percentage of hydroxy fatty acids in the oil, and quality and quantity of the seed meal.

Continued evaluation and further selection will be made within the progeny of the *Lesquerella fendleri* single plant selections currently growing at the Maricopa Agricultural Center. The effect of plant population density will be studied in replicated plots established within existing bulk seed planting. Plant spacings of 5, 7.5, 10, 15, and 20 cm within rows (double rows on 40" or 1 meter vegetable beds) will give populations of 100,000 to 400,000 plants/ ha. Seed yields will be determined and subsequent analysis for oil and hydroxy fatty acid contents made. Seed will be increased to provide for establishment of an experiment in October 1986 for determination of water use and cultural requirements.

A small observation planting of *Vernonia galamensis* from Kenya will be made at Phoenix and Tucson to evaluate its potential adaptation as a new crop for the production of vernolic (epoxy) acid.

REFERENCES

GENTRY, H.S. and BARCLAY, A.S. 1962. The search for new industrial crops III: Prospectus of *Lesquerella fendleri*. Econ. Bot. 16:206-211.

PERSONNEL

A. E. Thompson and W. J. Allen

Table 1. Performance of progeny from "Rapid Germination" cuphea selections. Seed planted 2/27/85.

Species	Number of progenies tested	Number of seeds planted	Number of progenies with germinating seedlings	Number of germinating seedlings	Number of seedlings producing seed
C. wrightii	556	27,455*	9	10	7
C. tolucana	29	1,450	7	24	6
C. paucipetala	4	200	1	2	0
Total	589	29,105	17	36	13

* A total of 17 progenies had less than 50 seeds/lot.

Table 2. Comparison of growth and flowering pattern of normal and compact *Cuphea leptopoda* plants. 1985, greenhouse data - 65 days after planting.

Characteristic measured		Normal plants (n=21)	Compact plants (n=17)	Difference (N-C)
Internode length (cm):	Internode #			
	0	2.04	1.35	0.69
	1	0.86	0.71	0.15
	2	1.50	0.91	0.59
	3	2.38	1.44	0.94
	4	3.76	2.35	1.41
	5	4.43	2.97	1.46
	6	4.55	2.88	1.67
	7	3.76	2.65	1.11
	8	2.79	1.94	0.85
	9	2.17	1.38	0.79
	10	1.76	0.91	0.85
	11	1.40	0.82	0.58
	12	1.12	0.68	0.44
	13	0.79	0.41	0.38
	14	0.50	0.24	0.26
	15	0.21	0.09	0.12
	16	0.12	--	0.12
Mean internode length (cm)		2.01	1.36	0.65
Total plant height (cm):		34.14	21.73	12.41
Branches/plant:				
Number:				
Primary branches		8.43	7.18	1.25
Secondary branches		3.48	0.24	3.24
Total		11.91	7.42	4.49
Mean length (cm):				
Primary branches		9.88	7.24	2.64
Secondary branches		2.18	2.50	-0.32
Total		12.06	9.74	2.32
Number of flowers/plant:				
Main stem		19.95	16.12	3.83
Branches		26.57	17.47	9.10
Total		46.52	33.59	12.93
Number of flowering branches/plant:		4.19	4.18	0.01

Table 3. Cuphea regional adaptation experiment — 1985, <u>Cuphea wrightii</u>-651.

Phenological data	Test locations									
	Corvallis OR	Ontario OR	Medford OR	Ames IA	Jacksonville IL	W. Lafayette IN	Beltsville MD	Experiment GA	Isabela PR	Phoenix AZ
Planting date:	5/16	5/23 (replant)	5/2	5/31	5/6	-[a]	5/22	5/7	5/24	4/24
Emergence:										
Date	6/5	6/4	5/17	6/7	5/17	-	5/27	5/17	5/31	5/2
Number of seedlings	53	214		2	161	-	-	56		35
2-Leaf stage:										
Date	6/15	6/10	-	6/17	5/31	-	6/10	5/24	-	5/14
Number of seedlings	191	220	-	54	86	-	92	57	-	40
6-Leaf stage:										
Date	7/6	6/20	-	6/28	6/10	-	6/25	6/3	?	5/24
Number of seedlings	170	248	-	50	95	-	72	55	-	37
Plant height(cm) H_1	5.5	4.7	-	3.5	24.1	-	5.0	5.5	10.5	6.0
Branching stage:										
Date	7/12	-	-	-	-	-	7/3	6/7	-	5/28
Flowering stage:										
Date	7/16	7/8	7/26	7/6	6/21	-	7/7	6/17	7/9	6/10
Plant height(cm) H_2	8.8	25.3	-	6.5	-	-	7.7	16.3	22.7	23.6
Seed ripening stage:										
Date	10/2	8/21	8/13	8/7	7/2	-	8/7	7/11	-	7/1
Plant height(cm) H_3	22.5	52.5	28.0	21.8	43.2	-	16.4	26.4	-	32.0
Harvest:										
Date (1st)	-[b]	9/9	10/1	-[c]	7/18[d]	-	10/7	8/5[e]	7/15	-[f]
Number of plants	-	-	46.8	-	-	-	47	24	-	-
Seed yield (g/1m row)	-	3.5	5.9	-	-	-	0.5	1.0	4.7	-
Date (2nd)	-	10/1	-	-	-	-	10/29	8/12	8/10	-
Seed yield (g/1m row)	-	2.4	-	-	-	-	0.1	1.2	4.2	-

[a] Plots disked up due to heavy weed population.
[b] Minimal plant growth and flowering - few seeds set.
[c] Seed ripening uneven and heavy rains in September and early October caused seed shattering. No harvest made.
[d] A total of 7 harvests made from 7/8 to 10/2/85. Minimal seed collected until around August 1.
[e] Heavy rains in July caused loss of most seeds by shattering.
[f] High daily temperatures prevented seed set. No harvest made.

Table 4. Cuphea regional adaptation experiment — 1985, *Cuphea laminuligera* (LA-002) and *C. lutea* (LU-001)

Phenological data	C. laminuligera				C. lutea			
	Corvallis OR	Ontario OR	Medford OR	Phoenix AZ	Corvallis OR	Ontario OR	Medford OR	Phoenix AZ
Planting date:	5/16	5/23 (replant)	5/2	4/24	5/16	5/23 (replant	5/2	4/24
Emergence:								
Date	6/5	6/4	-	5/2	6/8	6/4	-	5/2
Number of seedlings	9	83	-	32	27	10	-	15
2-Leaf stage:								
Date	6/17	6/10	-	5/14	6/18	6/10	-	5/14
Number of seedlings	192	93	-	34	183	30	-	14
6-Leaf stage:								
Date	7/8	6/20	-	5/24	7/9	6/20	-	5/24
Number of seedlings	166	101	-	38	176	39	-	11
Plant height(cm) H_1	5.0	3.2	-	6.7	4.5	2.4	-	4.6
Branching stage:								
Date	7/19	-	-	5/28	7/22	-	-	5/28
Flowering stage:								
Date	7/24	7/8	-	6/8	7/25	7/8	-	6/6
Plant height(cm) H_2	13.2	19.5	-	54.0	10.5	19.5	-	31.0
Seed ripening stage:								
Date	8/27	8/21	-	6/28	9/3	9/6	-	6/24
Plant height(cm) H_3	40.3	65.5	-	68.0	31.5	44.3	-	43.0
Harvest:								
Date (1st)	9/11	10/1	9/30	-	10/9	-[a]	9/30	-[b]
Number of plants	156	-	-	-	159	-	-	-
Seed yield (g/1m row)	1.3	1.7	6.6	-	6.6	-	4.2	-
Date (2nd)	10/9	-	9/19	-	-	-	9/19	-
Seed yield (g/1m row)	2.5	-	2.11	-	-	-	1.8	-
Date (3rd)	-	-	10/1	-	-	-	10/1	-
Seed yield (g/1m row)	-	-	3.2	-	-	-	3.4	-
Date (4th)	-	-	10/31[c]	-	-	-	10/31[c]	-
Seed yield (g/1m row)	-	-	1.1	-	-	-	0.2	-

[a] Plants senesced without significant seed yield.
[b] High daily temperatures prevented seed set. No harvest made.
[c] Seed harvested after frost on October 7-9.

Table 5. Status and distribution of cuphea germplasm collection, January 1, 1986.

	Distribution				TOTAL
	W. Roath Ames, IA	C. Jaworski Tifton, GA	S. Knapp Corvallis, OR	Retained in Phoenix, AZ	
Sections of genus - Number	8	6	1	7	8
Species - Total number	48	25	10**	32	48
- Number increased in Arizona	25	21	8	26	26
Accessions - Total number	185*	64	51**	99	189*
- Number increased in Arizona	69	47	24	67	77
Seed lots - Total number	283	68	62**	127	308
- Number increased in Arizona	89	51	29	87	115

* Includes 7 accessions and seed lots of unknown species.

** Includes 18 accessions and 20 seed lots from 6 species (Section-Heterodon) previously distributed 4/11/85 and 10/29/85.

Table 6. Evaluation of *Lesquerella* germplasm collection. Survival of transplanted and direct seeded plantings in central Arizona. Species grouped as to origin and type of hydroxy fatty acid produced in seed oils. Seeds germinated in greenhouse 7/3/84 for transplanting into field 10/1/84 - 90 Days after planting.

				Species transplanted (10/1/84)						Species direct seeded (10/1/84)			
				Number of seedlings obtained 15 DAP[a]	Plants surviving(%)-DATP[b]					Number of plants 25 DAP[a]	Plants surviving (%)-DAP[a]		
Species	Source of accession	Number of accessions received	1000 seed weight (g)		0	25	50	150	200		50	150	200
Lesquerolic Acid (C_{20}:1-OH):													
L. angustifolia	OK	3	3.24	336	93	92	85	12	0	558	77	20	1
L. argyraea	TX	4	0.68	95	96	93	88	27	7	194	82	15	5
L. engelmannii	TX	4	1.92	55	49	25	13	7	1	163	24	2	2
L. fendleri	TX,NM,AZ	26	0.64	426	52	32	25	22	21	2,545	38	15	16
L. globosa	KY,TN	1	0.83	0	--	--	--	--	--	--	--	--	--
L. gordonii	AZ,TX,OK	26	0.84	324	19	9	9	1	0	587	52	8	1
L. gracilis	TX,MS	3	0.76	132	66	63	54	8	0	599	56	5	3
L. grandiflora	TX	2	0.74	173	89	61	49	42	2	195	37	5	1
L. lasiocarpa	TX	2	0.65	23	90	90	90	87	0	16	88	81	12
L. lindheimeri	TX	1	0.93	--	--	--	--	--	--	--	--	--	--
L. ludoviciana	WY	1	1.19	40	65	48	45	32	0	23	0	0	0
L. mirandiana	MEX	1	0.93	1	--	--	--	--	--	--	--	--	--
L. ovalifolia	OK	1	1.30	2	50	0	0	0	0	--	--	--	--
L. palmeri	AZ	2	0.92	38	13	8	8	3	3	14	29	36	0
L. pinetorum	NM	1	1.11	41	37	37	37	29	29	130	12	5	5
L. purpurea	AZ	1	2.31	61	64	43	43	43	38	245	13	5	5
L. recurvata	TX	1	0.47	0	--	--	--	--	--	--	--	--	--
Total		80	1.14±0.17 CV = 62.5%	1,747	61	49	43	19	8	5,269	45	12	9
Auricolic Acid (C_{20}:2-OH):													
L. auriculata	OK	1	0.70	127	75	69	36	0	0	486	52	2	0
Densipolic Acid (C_{18}:2-OH):													
L. densipila	TN	3	0.83	71	93	48	31	0	0	149	3	1	0
L. lescurii	TN	1	0.99	2	50	50	50	0	0	--	--	--	--
L. lyrata	AL	1	0.58	36	94	61	16	0	0	0	0	0	0
L. perforata	TN	2	1.05	77	87	62	26	0	0	4	100	25	25
L. stonensis	TN	2	0.81	64	88	75	45	0	0	50	10	0	0
Total		9	0.85±0.08 CV = 21.5%	250	90	61	31	0	0	203	7	1	1
Total		90	1.06±0.13 CV = 59.6%	2,124	65	51	41	16	7	5,958	44	11	8

[a] DAP = Days after planting.
[b] DATP = Days after transplanting.

Table 7. Yield and plant measurements of 15 single plant selections of *Lesquerella fendleri* from direct seeded planting, with estimated yields of biomass, seed, seed oil, lesquerolic acid, and seed protein.

	Individual plant measurements					Estimated yields[a]-kilograms/hectare				
Plant selection number	Seed weight (g)	1000 seed weight (g)	Plant height (cm)	Dry weight of plant (g)	Harvest index	Biomass	Seed	Seed oil	Lesquerolic acid	Seed protein
330-10	19.7	.67	33	129	.15	19,350	2,955	739	443	680
333-1	17.7	.55	34	120	.15	18,000	2,655	664	398	611
330-18	14.2	.63	27	70	.20	10,500	2,130	532	319	490
330-5	12.7	.60	31	74	.17	11,100	1,905	476	286	438
330-7	12.2	.53	29	56	.22	8,400	1,830	458	275	421
330-19	10.6	.64	22	86	.12	12,900	1,590	398	239	366
283-4	9.2	.91	31	54	.17	8,100	1,380	345	207	317
330-13	8.9	.54	26	68	.13	10,200	1,335	334	200	307
324-2	8.2	.63	27	36	.23	5,400	1,230	308	185	283
330-16	8.0	.52	25	42	.19	6,300	1,200	300	180	276
284-3	7.8	.58	30	43	.18	6,450	1,170	292	175	269
330-4	7.3	.58	30	113	.06	16,950	1,095	274	164	252
330-15	7.1	.52	26	40	.18	6,000	1,065	266	160	245
330-1	6.4	.53	35	99	.06	14,850	960	240	144	221
333-2	6.4	.50	31	38	.17	5,700	960	240	144	221
Mean$\pm s_{\bar{x}}$	10.4±1.1	.60±.03	29±1	71±8	.16±.01	10,680	1,564	391	235	360
CV(%)	39	17	12	44	31					

[a] Estimated yields based upon plant population of 150,000 plants/hectare with 25% seed oil of which 60% is hydroxy oil (lesquerolic acid), and 23% seed protein.

TABLE 8. Linear correlations between yield and plant measurements of 15 single plant selections of Lesquerella fendleri.

	1000 seed weight (g)	Plant height (cm)	Plant dry weight (g)	Harvest index
Seed yield (g/plant)	0.204	0.280	0.612*	0.164
1000 seed weight(g)		0.059	0.066	0.081
Plant height (cm)			0.470	-0.278
Plant dry weight (g)				-0.650**

* Significantly different from zero at the 0.05 probability level.
** Significantly different from zero at the 0.01 probability level.

Table 9. Estimated yields and economic value of lesquerella grown as an industrial oilseed crop in the arid Southwest.

	Mean yield of selections	Yield of best selection	Breakeven yield
Yields (kg/ha):			
Seed	1,564	2,955	2,393
Oil	391	739	598
Seed meal	360	680	551
Dollar Value/Hectare:			
Seed oil @ $725/MT[a]	$283	$536	$433
Seed meal @ $130/MT[b]	47	88	72
Total	$330	$624	$505
Production Cost/Hectare[c]:	$505	$505	$505
Expected Return/Hectare:	-$175	$119	$ 0

a Based upon 5-year (1980-84) mean price of imported castor oil of $964/MT. Value of oil reduced to account for lower percentage of hydroxy fatty acid in lesquerella seed oil (60% vs. 80%).

b Based upon 9-year (1972-80) mean price of soybean meal (44% protein basis) of $193/MT. Value of meal reduced to account for lower percentage of protein in lesquerella seed meal (23% vs. 34%).

c Estimate based upon and adjusted from comparable production cost per hectare for wheat in Arizona (11): Seedbed preparation $35, cost of seed and seeding $25, irrigation $185, harvesting $50, seed cleaning $25, and fixed costs $185.

TITLE: CUPHEA GERMPLASM EVALUATION, DEVELOPMENT, AND DOMESTICATION

NRP: 20160 CRIS WORK UNIT: 5422-20160-004-01

INTRODUCTION

Species of cuphea have potential for domestication and development as a new crop for the production of lauric and other medium-chain fatty acids. The U. S. is dependent upon imports of coconut and palm kernel oils for its total supply essential to the manufacture of soaps, detergents, lubricants, and other related products. Field and laboratory experiments in Oregon in 1983 and 1984 indicate that cuphea has good prospects for agronomic adaptation. Slow emergence and seedling growth, seed dormancy, indeterminate plant growth and flowering, sticky plant hairs, and excessive seed shattering are the major constraints to domestication. A major breeding effort is needed to develop cultivars that will produce economically competitive yields of this important industrial oil.

PROCEDURE

The USDA/ARS, through a Specific Cooperative Agreement (SCA No. 58-9AHZ-3-744) with the Oregon State Agricultural Experiment Station, provides funding for research to develop cuphea as a new crop for production in Oregon and the Pacific Northwest. This is a unique, equally-funded, three-way effort of USDA/ARS, Oregon State AES, and member companies of the Soap and Detergent Association. Research funded under this SCA is conducted under CRIS No. 5422-20160-004-01, which is keyed to the inhouse CWU 5422-20160-004-00 at the USWCL in Phoenix, AZ. Dr. Anson E. Thompson serves as the ADODR on this SCA, and provides coordination and liaison within ARS and with state agricultural experiment stations and industry for all aspects of cuphea research.

A total of 6 projects are funded by and contribute to the research program in Oregon. Project titles and investigators are as follows:

1. Plant Breeding & Genetics - Dr. Steven J. Knapp
2. Agronomy - Dr. Gary D. Jolliff
3. Seed Dormancy & Technology - Dr. Donald F. Grabe
4. Weed Control - Dr. Arnold P. Appleby
5. Mechanical Harvesting - Prof. Dean E. Booster
6. Climatic Adaptation - Prof. Clinton C. Shock & Prof. John A. Yungen

RESULTS AND DISCUSSION

Initial USDA/ARS funding to this program for the amount of $25,000 was made in 1983. This amount was matched by the Proctor and Gamble Company with the Oregon State Agricultural Experiment Station providing equal support. Research on this program in 1983 was confined chiefly to aspects of plant breeding and weed control. A full-scale effort was launched in 1984 with the finalization of the total 3-way funding

package. A full, balanced, multidisciplinary research program was conducted in 1985. Detailed annual reports of the experiments are on file and available on request.

Oregon State University was successful in recruiting Dr. Steven J. Knapp, a very competent scientist, to replace Dr. Frank Hirsinger. Dr. Knapp started work on June 14, 1985, and quickly assumed responsibility for the breeding and genetic program as well as overall leadership for the whole program. It became readily apparent that the germplasm base upon which this program was operating was extremely narrow. Recorded information is not clear, but in all probability all of the Cuphea wrightii (acc. 651) material traced back to a single germplasm collection. The germplasm for the other 2 most promising species, C. laminuligera and C. lutea also most likely trace back to single accessions.

To overcome the deficit, limited quantities of seed of 17 accessions of 6 species [C. laminuligera (1), C. leptopoda (3), C. lutea (1), C. procumbens (2), C. tolucana (5), and C. wrightii (5)] were sent from Phoenix to Dr. Knapp, and incorporated into the working germplasm pool at Corvallis (See Table 1). Initial seed increases were made during the summer under cage isolation at Corvallis. Two of the new accessions of C. wrightii from the germplasm collection at Phoenix (A0077 or OSU #WR-002 and A0158 or OSU #WR-004) appear to be much better adapted than the existing material previously grown. Both flowered and matured seed earlier than the other accessions. The original accession 651 failed to produce an increase of seed in Corvallis.

At the end of the year, 42 seed lots of 5 additional species were sent to Dr. Knapp (Table 1). This included 36 seed lots of 27 accessions of C. lanceolata, which Dr. Knapp plans to evaluate for seed production capability when harvested by swathing. Preliminary results from harvesting a 2-meter section of the C. lanceolata (LN-002) plot in Corvallis by swathing on October 16th gave a seed yield equivalent to 355 kg/ha.

Seed of C. wrightii (acc. 651) was increased at Medford, OR. Approximately 85 pounds of seed were produced on 0.5 acre, and approximately 70 pounds are available for pilot processing studies at the Northern Regional Research Center in Peoria. The NRRC previously received 10 pounds of this accession produced in 1983 at Davis, Ca. Approximately 200 additional pounds of 4 1983 seed lots are now available for processing studies.

Crossing was initiated for pedigree and backcross/inbred breeding programs among the available accessions of C. wrightii, which is predominately self-pollinated. Seed was increased for recurrent mass and half-sib family selections within C. laminuligera, which is predominantly cross pollinated.

The effects of planting depths [surface (2 mm or less), 0.5, 1.0, and 2.0 cm] on seedling emergence and plant establishment of C. wrightii was evaluated in a replicated experiment. These planting depths had no

significant effect on emergence date or percent emergence, which is comparable to results obtained in 1984 (Table 2). Vacuum harvesting was experimentally compared with swathing plants of C. wrightii, C. lutea, and C. laminuligera. These preliminary results indicate that swathing to minimize seed shattering may be feasible with some species (Table 3).

An experimental 2-row, self-propelled vacuum harvester was designed, constructed, and tested with good results at 3 locations in Oregon. Refinements in various components are being made for evaluation in 1986.

Herbicide screening for effective weed control was initiated in 1983. Several herbicides have proved to be consistently safe on C. wrightii. However, these are most effective in controlling grasses, and control of broadleaf weeds has been less consistent. Additional research is needed to provide reliable information for making recommendations to cope with variations in growing conditions, weed populations, and different cuphea species grown for research or production.

Considerable effort was expended on various aspects of seed technology. Comparative studies of branching, flowering habit, and seed production of 5 cuphea species were conducted in the greenhouse. These data may lead to criteria of selection for concentrated flowering and seed production with less shattering and more efficient harvesting. Seed of C. wrightii is dormant at harvest and did not germinate without special treatment. Considerable dormancy was found to be still present in 1-year old seed, but essentially absent in 3-year old seed. Minimum and maximum temperatures for germination of C. wrightii seeds were 15 and 35°C, and light was required. Maximum germination required planting seed on blotters, at 20-30°C, in light, for a period of 3 weeks. Scarification by soaking seed for 10 minutes in concentrated H_2SO_4 was the most successful treatment for breaking dormancy of freshly harvested seed (Table 4). Priming or osmoconditioning of partially dormant 1984 seed with polyethylene glycol 8000 (PEG 8000) increased the speed of germination and raised total germination from 19 to 93% (Table 5). Priming was not effective on dormant 1985 seed.

The rates of seed development and maturation of C. wrightii and C. lutea were determined in greenhouse studies. The pattern of seed and oil development was similar in both species (Table 6). Maximum oil and dry matter contents were reached at 18 days after anthesis (DAA), with moisture content about 36%. C. lutea seeds attained higher quantities of both oil and dry matter. The carpels of C. wrightii opened 13 DAA and those of C. lutea at 14 DAA in the greenhouse. Maximum dry seed weight of C. lutea was reached in 20 days in the field, at which time the carpels also opened. Thus, seeds of this species developed maximum dry matter content by the time the carpels opened and exposed their seeds to shattering in the field.

SUMMARY AND CONCLUSIONS

Some slippage in the program was experienced with the change in personnel in the key position of plant breeding and genetics. Dr. Knapp, who

assumed the position in mid-year, has given the program new focus, and the program is judged to be fully on target. A major thrust of the program is to enlarge the germplasm base so that genetic advance is possible. It is apparent that additional germplasm collections will need to be made in both Mexico and Brazil.

Good progress is being made in the area of seed technology to better understand factors affecting seed dormancy and germination. Such information can have immediate application to stand establishment problems and application to timing of seed harvesting operations. The new acid scarification treatment holds promise for overcoming seed dormancy on newly harvested seed, which is very important in a breeding program.

The indeterminate, continuous flowering of most cuphea species results in production of seed with a continuous array of maturity. In _C. wrightii_ as well as some other species, the color of seed changes from green when the carpel opens to expose the seeds to yellow and to brown as the seeds mature. The higher quantity of chlorophyll in the seed coats of immature seeds may cause problems with oil extraction and require decolorization of the oils. The preliminary evidence that much of the seed's development, in terms of dry matter and oil content, occurs before the seeds are exposed to shattering may have considerable significance. This could be a factor in increasing seed yields through utilization of some harvesting techniques such as swathing. Additional research is needed to determine the effects of seed maturity on both oil quantity and the distribution of fatty acids in the oil.

With the production and availability of over 250 pounds of seed of _C. wrightii_, laboratory scale extraction studies can be initiated at the North Central Regional Research Center in Peoria. This will provide oil and meal samples for utilization research.

Dr. Steven J. Knapp will assume the position of Principal Investigator on the project. He is making plans for a collection of additional accessions of several species in Mexico during August-September 1986, to provide a more adequate germplasm base for the program. Primary emphasis will be on obtaining more material of _C. wrightii_, _C. laminuligera_ and _C. lutea_. A systematic effort on germplasm maintenance, enhancement, and breeding is underway with special emphasis on the 3 species listed above. Mating systems research needed for development of efficient procedures for germplasm handling and multiplication will also be initiated with these 3 species. Twenty eight accessions of _C. lanceolata_ obtained from the germplasm collection in Phoenix will be evaluated for seed production potential of plants harvested by swathing.

Dates of planting studies will be conducted to determine effects of soil temperature on stand establishment and the effect of planting dates on dates of seed harvest. The effects of seed priming and dormancy-breaking treatments will be studied to improve germination of recently harvested seed and germination at cooler soil temperatures. Seed and environmental factors will be studied to determine the nature of dormancy and possibilities of its modification and management. Additional

research will be conducted on development of cultural practices and evaluation of germplasm for adaptation. Refinements will be made on the vacuum harvester and it will be extensively tested during the cropping season.

The program will continue to participate in the regional adaptation trials, and special emphasis will be made in Southern Oregon as well as the Willamette Valley. Plans are being made to have a field day and meeting in late August or early September to visualize and evaluate progress in the research program.

REFERENCES

KNAPP, S. J. (ed.). 1985 Annual Report: Cuphea domestication and agronomic development in Oregon. Department of Crop Science, Oregon State University. Dec. 12, 1985. 63 pp.

PERSONNEL

A. E. Thompson, ADODR; G. D. Jolliff, Principal Investigator, and S. J. Knapp (Oregon State University, cooperators).

Table 1. Cuphea germplasm sent to Oregon State University - 1985.

USDA/ARS Phoenix,AZ	OSU No.	Species	Original designation and and source of seed	Number or weight of seed
A 0312	GL-001	C. glosostoma	Original seed - F. Hirsinger	20
A 0076	NF-001	C. inflata	G-724 Original seed	50
"	NF-002	"	" 1983-84 GH Inc.	50
A 0142	LA-007	C. laminuligera	G-803 1983 Field & 83-84 GH Bulk	1.80 g
A 0058	--	C. lanceolata & C. procumbens admixture	G-704 & G-709 Original seed	2.06 g
A 0207	LN-008	C. lanceolata	G-1 G. Robbelen 1982 GH Inc.	10
"	LN-035	"	" " 1984 GH Inc.	30
A 0208	LN-009	"	G-3 " 1982 GH Inc.	10
A 0209	LN-010	"	G-4 " 1982 GH Inc.	10
A 0210	LN-011	"	G-5 " 1982 GH Inc.	10
A 0211	LN-012	"	G-19 " 1982 GH Inc.	40
"	LN-036	"	" " 1984 GH Inc.	0.96 g
"	LN-034	"	" " 1984 Field Inc.	1.30 g
A 0212	LN-019	"	G-20 " 1982 GH Inc.	10
A 0214	LN-020	"	G-23 " 1982 GH Inc.	30
"	LN-032	"	" " 1984 Field Inc.	40
A 0215	LN-021	"	G-24 " 1982 GH Inc.	25
A 0216	LN-022	"	G-25 " 1982 GH Inc.	30
"	LN-031	"	" " 1984 Field Inc.	2.16 g
A 0217	LN-023	"	G-26 " 1982 GH Inc.	20
"	LN-030	"	" " 1984 Field Inc.	75
A 0218	LN-024	"	G-27 " 1982 GH Inc.	30
A 0219	LN-025	"	G-31 " 1982 GH Inc.	10
A 0220	LN-026	"	G-32 " 1982 GH Inc.	30
"	LN-029	"	" " 1984 Field Inc.	40
A 0221	LN-013	"	G-35 " 1982 GH Inc.	30
"	LN-033	"	" " 1984 Field Inc.	3.32 g
A 0222	LN-014	"	G-36 " 1982 GH Inc.	40
A 0223	LN-015	"	G-38 " 1982 GH Inc.	20
A 0224	LN-016	"	G-39 " 1982 GH Inc.	40
A 0225	LN-017	"	G-40 " 1982 GH Inc.	20

Table 1. Cuphea germplasm sent to Oregon State University - 1985, (con'd)

USDA/ARS Phoenix,AZ	OSU No.	Species	Original designation and and source of seed	Number or weight of seed
A 0226	LN-018	"	G-42 " 1982 GH Inc.	20
"	LN-037	"	" " 1983 Field Inc.	4.12 g
A 0227	LN-003	"	G-44 " 1982 GH Inc.	10
A 0228	LN-004	"	G-45 " 1982 GH Inc.	30
A 0229	LN-005	"	G-47 " 1982 GH Inc.	30
A 0230	LN-006	"	G-48 " 1982 GH Inc.	30
A 0231	LN-007	"	G-50 " 1982 GH Inc.	30
A 0252	LN-028	"	F. Hirsinger 1981 Gottingen	2.32 g
A 0308	LN-027	"	NU 42430 G. White-BARC 1970 Inc.	100
A 0065	LE-002	C. leptopoda	G-713 1983 GH Inc.	1.20 g
"	LE-003	"	" Compact sel. 1983 GH Inc.	0.15 g
A 0070	LE-004	"	G-718 1983-84 GH Inc.	0.90 g
A 0072	LE-005	"	G-720 1983 GH Inc.	4.40 g
"	LE-006	"	" Compact sel. 1983-84 GH Inc.	0.015 g
A 0144	LU-004	C. lutea	G-806 1984-85 GH Inc.	40.00 g
A 0100	PR-001	C. procumbens	G-752 1983-84 GH Inc.	4.40 g
A 0235	PR-002	"	G-11 G. Robbelen 1984 Field Inc.	0.20 g
A 0263	PR-004	"	F. Hirsinger-nonsticky 1984 GH Inc.	50
A 0263-2	PR-005	"	Pink flower-nonsticky sel. 1984 GH Inc.	50
A 0044	TL-007	C. tolucana	G-475 1982 GH Inc.	0.15 g
A 0047	TL-008	"	G-629 1982 GH Inc.	0.21 g
A 0048	TL-009	"	M&K 20570 Original seed	0.18 g
A 0090	TL-010	"	G-741 1982 GH Inc.	0.14 g
A 0111	TL-011	"	G-763 1982 GH Inc.	0.17 g
A 0050	WR-001	C. wrightii	G-501 1983-84 GH Inc.	1.40 g
A 0077	WR-002	"	G-725 1983-84 Field & GH Bulk Inc.	21.70 g
A 0084	WR-003	"	G-732 1983-84 GH Inc.	3.10 g
A 0158	WR-004	"	G-828 1984 Field Inc.	2.40 g
A 0243	WR-005	"	G-62 G. Robbelen 1983-84 GH Inc.	37.40 g
A 0255	WR-006	"	F. Hirsinger (Probably G-651) 1982 Davis, CA (Plot 30)	6.70 g
A 0049	VS-001	C. viscosissima	Balogh 912 1983 GH Inc.	100

Table 2. The effect of planting depths on seedling emergence of *Cuphea wrightii*. Corvallis, OR - 1985.

Planting depth	Date of emergence	Percent emergence
Surface (2 mm or less)	June 6	77.6
0.5 cm	June 6	73.5
1.0 cm	June 5	89.6
2.0 cm	June 5	76.7

Table 3. The effects of harvest date and method on seed yield (kg/ha) of cuphea species. Corvallis, OR - 1984 and 1985.

Harvest Date	*C. laminuligera*		*C. lutea*		*C. wrightii*		
	Swathed	Vacuum	Swathed	Vacuum	Swathed		Vacuum
	1985	1985	1985	1985	1984	1985	1985
Sept. 3	19.8	-	-	-	-	-	-
Sept. 11	35.0	9.7	-	-	-	-	-
Sept. 18	13.0	-	-	-	-	-	-
Sept. 25	18.4	-	23.9	-	-	-	-
Oct. 2	42.9	-	87.4	-	139.0	2.0	0
Oct. 9	56.7	13.8	107.6	45.0	196.0	2.9	0
Oct. 16	31.1	-	102.1	-	92.0	2.1	0

Table 4. Effects of seed treatments on germination of Cuphea wrightii seed. Corvallis, OR - 1985.

Treatments	Germination percentage 1982 seed	1984 seed	1985 seed
Control	68	13	0
Kinetin - 20 ppm	68	18	0
GA_3 - 100 ppm	69	27	0
KNO_3 - 0.2%	75	24	0
Thiourea - 0.1%	65	18	0
Ethephon - 25 ppm	75	19	0
Prechill - 5°C	-	-	1
Dry heat - 40°C - 21 days	-	-	0
Scarification:			
Mechnical - chipping	-	-	16
Acid - conc. H_2SO_4 - 10 min.	-	-	63
Acid scarification + Kinetin	-	-	27
" " + GA_3	-	-	20
" " + KNO_3	-	-	21
Acid scarification + prechill	-	-	35
" " + " + Kinetin	-	-	48
" " + " + GA_3	-	-	24
" " + " + KNO_3	-	-	41
Acid scarification + dry heat	-	-	33
" " + " + Kinetin	-	-	45
" " + " + GA_3	-	-	31
" " + " + KNO_3	-	-	35

Table 5. Effect of priming Cuphea wrightii seed of different ages in PEG 8000 at 25°C with an osmotic potential of -12.5 bars on percentage and rate of germination at 15 and 25°C. Corvallis, OR - 1985.

Priming treatment	Days germinated	Germination percentage 1982 seed 15°C	1982 seed 25°C	1984 seed 15°C	1984 seed 25°C	1985 seed 15°C	1985 seed 25°C
Control:	3	31	71	1	10	0	-
	10	76	77	20	12	0	-
	16	79	85	46	19	0	-
Primed:	3	79	65	25	89	0	-
	10	83	68	87	91	0	-
	16	97	71	87	93	0	-

Table 6. Time course of seed development in <u>Cuphea</u> <u>wrightii</u> and <u>C.</u> <u>lutea</u> in greenhouse and field. Corvallis, OR - 1985.

Time after anthesis	Seed dry weight mg/seed			Dry matter %			Oil content %		Oil content mg/seed	
days	wrightii GH	lutea GH	lutea Field	wrightii GH	lutea GH	lutea Field	wrightii GH	lutea GH	wrightii GH	lutea GH
5	0.31	0.48	0.29	16.1	16.2	13.9	44.8	65.8	0.14	0.32
6	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-
8	0.49	0.70	0.33	21.8	22.9	19.2	32.6	31.3	0.16	0.22
9	-	-	-	-	-	-	-	-	-	-
10	0.91	-	0.42	35.9	-	36.7	35.9	-	0.33	-
11	-	1.42	-	-	40.1	-	-	42.2	-	0.60
12	-	-	0.66	-	-	47.3	-	-	-	-
13*	1.52	-	-	58.1	-	-	44.9	-	0.68	-
14**	-	2.36	1.08	-	57.3	55.1	-	42.5	-	1.00
15	-	-	-	-	-	-	-	-	-	-
16	-	-	1.43	-	-	56.4	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-
18	1.90	2.70	1.66	63.4	64.6	61.1	43.8	43.2	0.83	1.17
19	-	-	-	-	-	-	-	-	-	-
20***	-	-	1.97	-	-	55.2	-	-	-	-
21	1.87	-	1.95	62.7	-	52.6	45.2	-	0.85	
22	-	-	-	-	-	-	-	-	-	-
23	-	2.67	-	-	63.3	-	-	37.8	-	1.01
24	1.88	-	1.96	61.9	-	62.3	41.2	-	0.71	-
25	-	-	-	-	-	-	-	-	-	-
26	-	2.68	-	-	65.0	-	-	41.2	-	1.10

* Date when carpel opened to expose seeds - C. wrightii - greenhouse.
** Date when carpel opened to expose seeds - C. lutea - greenhouse.
*** Date when carpel opened to expose seeds - C. lutea - field.

TITLE: BORDER IRRIGATION DESIGN AND CONTROLS

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION

Border irrigation is a complex physical process which has defied scientific description and control. Border irrigation can be described as gradually varied unsteady open channel flow over a porous media with time-dependent infiltration (outflow). Recent advances in mathematical modeling have made it possible to simulate border irrigation flow under some fairly general conditions. However, methods for control of such systems are still not very well developed. In general, the factors which affect border irrigation performance can be broken down into three categories (Strelkoff, 1985):

1. Design parameters that are physically fixed for an irrigation season, namely: field length, and slope. The field end condition, open ended or blocked, is usually decided during design, although it could be altered during the growing season.

2. Management parameters that the irrigator has direct control of, namely; irrigation stream size per unit width of border, length of irrigation set (cutoff time) and management allowed deficit (depth of water to be applied).

3. Soil and crop factors which can be controlled to a very limited degree, namely, surface drag or roughness and soil infiltration characteristics.

The important differences in these three groups of variables will be discussed in later sections.

The purpose of the paper is to present the problems associated with the design of border strip irrigation systems and to offer some useful approaches toward developing better design methods. This paper also discusses problems with the operation of border irrigation systems, and some new and innovative techniques that are being used to solve this difficult contol problem.

BORDER OPERATIONS

Under border or border strip irrigation, water is applied to one end of a strip of land bounded by soil dikes or borders. Water advances from one end to the other. The downstream border end can be either open or blocked. When blocked, the stream must be cut off in time such that the downstream dike is not overtopped by the water ponded behind it. When open, the flow is usually cut off before the advancing stream reaches the end to limit the amount of runoff or tailwater. Having water on one end of the border longer than the other can cause differences in the infiltrated depth of water, usually resulting in excess infiltration and

deep percolation. Border irrigation operations attempt to select a stream size and cutoff time so as to minimize both deep percolation and runoff, while still providing a sufficient amount of water to most of the field.

The U. S. Soil Conservation Service (SCS) criterion on design and operations is to provide enough opportunity time at the upstream or head end of the border (USDA, 1974). This opportunity time is simply the application time plus the time required to dewater the head end after cutoff, the latter of which is known as the recession lag time. If the recession lag time can be determined and an estimate of potential efficiency is available, then the appropriate stream size to put on the necessary volume can be computed. Such an approach attempts to place all of the error in the irrigation to the far end of the field. This can result in large runoff volumes or deficits in infiltrated depth at the downstream or low end.

Several researchers have proposed empirical design/operation procedures for borders based on the premise that the recession curve is not affected by the inflowing stream size and is only effected by slope and roughness (Bowman, 1973, and Merriam, 1978). This is probably a reasonable supposition, since once water has started to recede, the surface storage volume near the receding edge should be relatively independent of prior conditions. Fangmeier (1978) found that recession lag time was predominately governed by slope and roughness, with other variable directly explainable through dimensional analysis. Under both Bowman's and Merriam's approaches, the stream size is determined by matching the water advance and recession curves (i.e., making the parallel), the difference between curves at any location being the infiltration opportunity time. Both approaches require an estimate of the recession curve. Merriam proposes some general recession curves, which are modified by relative intake, slope, retardance (roughness), management allowed deficit, and stream size. Taking the advance curve parallel can result in too much runoff if the field is too short or too much infiltration if the field is too long. These procedures are essentially methods for making recommendations for existing systems, not necessarily for new designs. Neither method provides much insight into the amount of recession lag time and its effects other than through empirical observation.

PERFORMANCE MEASURES

Border irrigation performance is generally described by some kind of efficiency or uniformity term. Assuming a uniform deficit of required water, an idea irrigation would infiltrate and store the exact amount of water required to refill soil moisture storage (or some lesser desired depth). In practice, this is not possible to do with surface (or any other type) irrigation systems. A nonuniform distribution of water will result in some over application of water (deep percolation), some under application of water (deficit irrigation), or both. More uniform applications of water can usually be achieved by using large stream sizes resulting in rapid advance and more uniform infiltration opportunity

times. This often results in large runoff volumes which must be stored for reuse or allowed to flow into natural water courses with possible detriments to receiving water quality.

The most frequently used measures of border irrigation performance (Kruse, 1978) are the Application Efficiency, AE (ratio of the average depth of water stored in the root zone to the average depth of irrigation water applied), the Irrigation Efficiency, IE (ratio of the average depth of water beneficially used to the average depth of water applied), and the low quarter Distribution Uniformity, DU (ratio of the average low quarter depth of water infiltrated to the average depth of water applied). Some deficit is frequently allowed over small portions of the field so that the deep percolation and runoff are kept down to reasonable levels. Some means of providing adequate leaching over this area must be provided if sustained crop production is desired.

It should be noted that the are three ways in which an irrigation can deviate from ideal; 1) excess infiltration (e.g., deep percolation), 2) runoff, and 3) deficits from the desired amount. The importance of each of these factors will be different in different geographical areas. Performance measures should be selected which are reasonable for the farmers values as well as those of the community at large. Any theoretical analysis under one set of criteria may not be totally applicable under another.

In general, the variability of soil properties causes some differences in actual uniformity from that which may be computed theoretically. One performance measure that partially takes this into account is the low quarter distribution uniformity. A similar measure, the low quarter application efficiency (AELQ) defined as the average low quarter depth infiltrated and store divided by the average depth applied, is often useful. In theoretical studies it is useful to use the Potential low quarter application efficiency (PAELQ) where the low quarter depth infiltrated is the same as the desired depth. This limits errors from relying on a single depth, such as the minimum depth, for a performance measure.

BORDER DESIGN CONCEPTS

In designing border irrigation systems, the two most limiting constraints are usually soil conditions and topography. Here we will consider only graded border strips and not less controlled irrigation methods such as contour flooding. Shallow topsoils can severely limit the amount of land grading that can be done. My own prejudice is to put the border strip on as flat a slope as is feasible. This will limit erosion potential and will usually provide more positive control (or more stable values) of uniformity, which will be demonstrated in a later section. For a given site and design efficiency, this will often result in short border strip lengths. Under some conditions such short borders strips are not feasible. On steeper slopes, such contouring may result in border strip widths than are not feasible. Thus some compromise on slope is often necessary.

The layout of border strips must also account for variations in soil texture and resulting changes in soil water holding capacities and soil infiltration properties. Soil variation and depth of top soil considerations are often more important than slope considerations. For many sites, some reclamation of soil properties is necessary where significant mounts of top soil are removed. Soil swapping has been used successfully in some areas to remove pockets of dissimilar soils. This is more significant on flatter slopes (e.g., level basins) where actual ponding of water takes place.

Two other limitations of border strip layout are the available water supply and available labor. Limited supply flow rates or stream sizes can limit the width of the border strips, since design is generally based on stream size per unit width of strip. In general, steeper slopes and shorter strips require smaller unit stream sizes. Thus, some tradeoff between strip width and strip length (and slope) may be necessary where stream sizes are limited. Labor imposes a different kind of constraint which is often not considered in design. Ideally, the stream size and cutoff time for a given border strip could be theoretically determined and followed by the irrigator. In practice, the stream size generally remains fixed and the irrigation sets are changed according to a convenient labor schedule (e.g., every 8 or 12 hours). The possibility of such real constraints should be considered in design.

For a given field length and slope, and a specific range of soil infiltration and roughness conditions, there is a very limited range of soil moisture deficits which can be handed with a reasonable efficiency. In the design process, the field length and slope must be selected such that this deficit is reasonable. Surface irrigation systems are often designed for relatively large depletion level compared to non-surface methods. In some cases this limited flexibility in application depth makes surface irrigation a less desirable method. The operator must select a stream size and time to apply the deficit efficiently, which is usually done by trial and error.

Infiltration poses the biggest single problem in the design and operation of border irrigation systems. The major problems related to infiltration are

1. Quantifying the infiltration of water into a soil which is to be surface irrigated and has not been previously surface irrigated.

2. Quantifying changes in infiltration over the growing season.

3. Estimating changes in infiltration from season to season as a result of land use and farming practices.

4. Quantifying the effects of tillage and farm machinery traffic on infiltration.

5. Quantifying the effects of spatial variations in infiltration on the measures of irrigation performance.

Detailed analysis of all these factors is well beyond the scope of existing design practice, in terms of both feasibility and cost effectiveness. Thus in the design process, values for infiltration are typically simply chosen as representative and used as known fixed values in the remainder of the design.

INFILTRATION CHARACTERISTICS

To aid in this design process, the SCS developed a means of classifying the infiltration characteristics of soils (USDA, 1974). Soils are grouped into "Intake Families" by numbers which represent infiltration rate (e.g., 1.0 in/hr). Soil series classifications are often given intake family values or ranges to provide relative information in planning. Local experience with irrigation on given soil types provides better information on design. Even better is infiltration data collected on the site to be designed.

The SCS intake family functions are of the following form

$$Z = c + k\ t^a \tag{1}$$

where Z in cumulative infiltration depth, t is infiltration opportunity time, and c, k, and a are empirical constants. The value of c in the SCS family functions is relatively small (0.275 in or 7 mm) and has a minor impact on the function. A simple power function proposed by Kostiakov (1932) is often used instead where

$$Z = k\ t^a \tag{2}$$

The value of k is the intercept at unit time on a log-log plot of Z versus t and varies considerably from site to site. The value and significance of k depend somewhat on the time unit chosen. Hours is a convenient time unit since the value of z at one hour can be a significant value.

The value of the exponent, a, theoretically varies from 0.0, for instantaneous infiltration followed by surface sealing to 1.0, for a constant infiltration rate. The SCS family exponents range from 0.661 to 0.823, a fairly narrow range. In practice, the exponent can vary from below 0.1 for cracking soils to around 0.8 for well drained soils, with a majority of reported values in the range 0.3 to 0.6. (Clemmens, 1978). Simple piston flow models for a wide range of soils predict infiltration exponents in the range of 0.35 to 0.75 depending on the values of soil properties chosen, with exponents between 0.5 and 0.7 for a majority of conditions (Clemmens, 1977). This indicates that infiltration into many soils does not follow simple piston flow. Theoretical prediction of soil infiltration would therefore be particularly difficult from both a modeling and a data collection standpoint which would not be feasible under current border irrigation practice.

The infiltration exponent, a, indicates the shape of the cumulative infiltration function versus time. Any differences in opportunity time

along the border would result in differences in infiltrated depth. The amount of these differences (assuming uniform soil infiltration conditions) is greatly affected by the shape of the infiltration curve. For a given range of infiltration opportunity times, the smaller the infiltration exponent, the less the relative difference in infiltrated depth. At a = 0.0, all opportunity times give the same depth. At a = 1.0, depth is linearly related to opportunity time. To demonstrate the effects of this exponent on border irrigation flow, consider the example infiltration curves shown in Figure 1 (taken from Clemmens, 1981a). Ring infiltration data was taken during the irrigation. The data were adjusted to give a volume balance by a method similar to that proposed by Merriam (1971). Even with this method four different infiltration functions were postulated as satisfying the volume balance (Clemmens, 1981a). Note that all four of these curves cross at roughly the same point somewhere between the minimum and maximum infiltration opportunity times on Figure 1. The SCS had classified the soil as being in the 1.0 to 1.5 in/hr intake category. The SCS intake curves are shown in Figure 1. The zero inertia border irrigation model (Strelkoff and Katopodes, 1977) was used to simulate irrigations with 6 different infiltration functions for three different borders as shown in Table 1 (opportunity times in Figure 1 are from Basin 7). It is significant to note that with the higher initial infiltration, that the predicted advance did not reach the border end for basins 2 and 8, while it did reach the field end for the other infiltration functions. While this example was for a level border or basin, the effect is still significant for sloping borders. It is also worth noting the differences in the range of infiltrated depths as indicated by the minimum and maximum opportunity times for the four infiltration functions.

The use of a power (exponential) function for describing infiltration is admittedly approximate. Clemmens (1983) studied the use of a number of infiltration functions and their ability to represent actual measured infiltration. The conclusions of that study were 1) that the theoretical equations such as Philip's and Green-Ampt equation were inadequate at fitting real infiltration data under border irrigation, 2) that the SCS equation adds an extra parameter with no improvement in describing infiltration, 3) that the Horton equation was very poor for fitting infiltration rate data and should not be used, 4) that the simple Kostiakov function could be used for most cases, 5) that where soils exhibit a final infiltration rate, the addition of a third parameter with either the Kostiakov branch or modified function was most appropriate, and 6) that the Collis-George equation matched infiltration data well but had no particular advantage over the Kostiakov formulations. The Kostiakov modified function has been used by many and is of the form

$$Z = k\ t^a + ct \tag{3}$$

The Kostiakov branch function has been used by Clemmens (1981a and 1983), Clemmens and Dedrick (1981) and for surge flow by Izono and Podmore (1985), and is of the form

$$\begin{aligned} Z &= k\ t^a & t &\leq t_c \\ Z &= k\ (1-a)t_c{}^a + ct & t &> t_c \end{aligned} \tag{4}$$

This later function gives a constant infiltration rate after time t_c, while for Eq. (3) a final infiltration rate is simply approached.

INFILTRATION EFFECTS ON DESIGN

The key to the use of any infiltration function for border irrigation is to know the amount of time that is required to infiltrate the desired depth of application. Design (or operation) is then simply a matter of providing that much opportunity time everywhere along the border. As noted in Figure 1 and the prior discussions on the range of infiltration exponents, the SCS intake families are not very appropriate for describing border infiltration. A new set of infiltration families was proposed by Merriam and Clemmens (1985) to overcome these shortcomings. An approximate relationship was found for non-crcking soils between the time required to infiltrate 100 mm (4 in) and the exponent, a. With this, a set of time-rated infiltration curves were developed to more nearly approximate the shape of actual infiltration functions. When used within a limited range, these equations should be adequate for many border designs. No curves were presented for cracking and unusual soils since the possible intake characteristics vary so widely.

One potential use of border irrigation models is in the development of potential efficiencies for a given set of conditions. However, the misuse of such optimum efficiency curves can lead to problems. A set of optimum efficiency curves for a specific case are shown in Figure 2 (Clemmens,1979). As can be seen, at higher slopes the efficiencies are slightly higher, but the range of flow rates for achieving that efficiency are smaller. Figure 3 shows the same curves for the same conditions with different infiltration conditions. Note that the efficiency curves at the greater slopes now have very narrow peaks. These two infiltration conditions were measured on the same field during the same growing season. If design and operations were based on a the first set of infiltration conditions (i.e., greater slopes), attaining reasonable efficiencies during the second set of infiltration conditions would have been extremely difficult, particularly if the change in infil tration was not anticipated beforehand.

One approach to design under these conditions would be to select a slope based on maximum efficiency and assume that the irrigator will be able to make the appropriate adjustments when conditions change. This would require an assessment of both infiltration and roughness, the later of which was not considered in the foregoing example. Currently, this is beyond the scope of most irrigators, and will be discussed in more detail in a later section. A better approach is to design so that a reasonable efficiency can be obtained over a wide range of conditions. Then if the irrigator develops the sophistication to modify stream size and time in response to changing conditions higher efficiencies can be attained. This approach minimizes the possibility of poor performance during parts of the season which might force the irrigator to abandon, over most of the season, otherwise good recommendations.

The SCS has published a set of attainable efficiency values for border strips which attempt to give reasonable guidelines on design. They have not specifically considered ranges of variables and their effect on efficiency, but rather have given some conservative estimates of the efficiency peaks. Shatanawi and Strelkoff (1984) as well as others warn against the use of such single valued efficiency peaks due to the presence of efficiency "cliffs". Such efficiency cliffs are demonstrated by the failure of the stream to advance to the end of the border as shown in Table 1, and by the sharp decline in efficiencies shown in Figures 2 and 3. Both these examples are for blocked end borders. The efficiency cliffs for open ended borders can be much steeper.

To date, a comprehensive set of efficiency contours or curves has not been produced. The modeling techniques and dimensional analysis theories are now available (Strelkoff, 1985 and Clemmens, 1981b). It is simply a matter now of determining which of the many ways to express these relations is most useful and then to generate these curves from simulation data (with some curve fitting and transformation required to limit the number of runs). This has been proposed since 1981 (Clemmens, 1981b). With the completion of the new Border Flow model and adaptation to the USWCL computer system, this work will be initiated in 1986. The results of this work will almost certainly provide considerable insight into the design process.

OPERATIONAL CONTROL

Operational control of border irrigation systems can be difficult as outlined in the previous sections. Generally, the stream size and cutoff time are determined prior to the irrigation. There are several approaches to control. First, irrigations can be observed and adjustments made on subsequent irrigations. With infiltration and roughness changing over the season, this can prove time consuming and difficult, often requiring years of experience. One aid in this process is the use of advance ratios (Merriam, 1980 and Clemmens and Dedrick, 1981). The advance ratio is the ratio between advance time and the opportunity time at the end of the border. When this ratio is on the order of 1/4, the water distribution is probably very uniform. This is affected by both the infiltration exponent and the shape of the advance curve. Measurement of runoff and opportunity times are necessary to make this method effective.

Often, the stream size is not changed and the irrigator simply turns the water off when it reaches a certain distance down the border, typically 2/3 to 3/4 the length. If the stream size is reasonable this method can work well. On many systems with low infiltration rates, this is not feasible since the water advance is so much slower than the relative infiltration. Under such systems, advance is completed long before cutoff, and unless the stream is cutback to a lower flow rate, large amounts of runoff will result.

Another approach would be to observe advance on one border and determine appropriate adjustments to subsequent borders. This can be done by

someone who has a lot of knowledge gained through experience or who has good knowledge of irrigation hydraulics. This is not common among irrigators who would probably need some detailed guides on how and when to make adjustments. One problem with this is that the flow to a border may be cut off long before the irrigation is over. Thus the evaluation is delayed, and probably not much use even on the next border. Spatial variations in soil properties from border to border can make this approach less effective.

A third approach would be to make some measurements of infiltration (and roughness) prior to the irrigation. With these estimates, an optimum stream size and cutoff time would be determined from some procedure. This is a viable method except that 1) no simple methods are available for accurate assessment of infiltration prior to irrigation, and 2) no simple methods are available for determining the optimum stream size and time. Reasonable estimates can be made with some experience or from running irrigation simulation computer programs. Many irrigators do not have enough experience nor access to computer models to make this feasible, even if they did have intake measurements. Recommendations would have to come from consultants (Private or Government). These optimum stream size and time values could be generated for any given set of conditions and performance criteria from existing computer models. Dimensional analysis would be needed for a display of all pertinent variables in a reasonable number of curves and graphs (or equations). This is frequently referred to as the optimizaton phase of control.

A new approach to control (new in practice but not new in theory) is to use measurements made during advance to first estimate infiltration conditions and roughness (identification phase) and then adjust the stream size to achieve the optimum irrigation performance (optimization phase). This approach has an advantage in that it provides real time feedback and control. However, there are a number of significant problems that will have to be overcome.

REAL TIME PARAMETER IDENTIFICATION

The basic idea of parameter identification is to use information from the stream advance to estimate the values of the unknown parameters for roughness and infiltration. This is analogous to what is referred to as an inverse problem, where simulation model output is compared with real world output in order to arrive at some input parameters' values. For the border irrigation problem, there are two factors which make this problem particularly difficult. First, the border irrigation advance problem is poorly posed, that is nearly identical output conditions could result from significantly different input conditions. This is complicated by the spatial variations in infiltration and roughness properties, by nonuniform surface conditions, and by measurement errors. The second problem is related to infiltration. Without prior knowledge of infiltration properties, predicting an infiltration function for the entire irrigation from data collected during a short period of advance can be very misleading. It amounts to extrapolation with an assumed

infiltration equation. In general, simple infiltration equations (e.g., Kostiakov) do not do a good job of fitting infiltration at very short times.

Several researchers have approached the surface irrigation inverse problem. To date, no significant progress has been made, however research in this field has some promise. On one extreme, some researchers are exploring the problem with the simplest models possible with the hope of being able to develop a means of field calibrating a parameter estimation procedure. At the other extreme, one researcher is using only theoretical models in an attempt to determine how many parameters must be measured to predict the correct values of roughness and infiltration. Some of this work is summarized below.

In border advance, an increase in surface roughness or drag from some assumed value will cause advance to slow down and the surface water depth to rise from that at the assumed value. In contrast, an increase in infiltration (e.g., the constant k) will cause advance to slow and will cause the water depth to drop. Thus roughness and infiltration affect advance rates and water depths differently. Preliminary evidence from Katopodes (1985) indicates that advance measurement alone are not sufficient to separate infiltration and roughness effects for borders under the assumptions of the zero-inertia model, even with "perfect" data. He also concludes that measurements of the upstream depth are sufficient to determine the value of the roughness parameter n (Manning n), but that without information on the shape of the stream profile the values of k and a for infiltration cannot be uniquely determined. With two measurements of depth and a known roughness value, k and a could be uniquely determined. Using the upstream depth alone to estimate the roughness value can lead to erroneous results for all parameter values, since they are sensitive to small errors. The exact number and type of measurements needed is not known at this time.

Reddell (1981) from Texas A&M proposed a system for providing real time control of furrow irrigation systems. Furrow systems differ from borders in that water flow is channeled and less restricted by vegetation such that advance is considerably faster. Under furrow irrigation high runoff volumes are more common. Cutback schemes, where the inflow is cut roughly in half after advance, and surge flow where the inflow stream is cycled, are both used to reduce runoff. One scheme proposed by Reddell (1986) is to allow one cycle of surged inflow to infiltrate, recording the volume applied and the advance distance. This would remove the problem of surface storage and roughness estimation. A similar possibility was suggested by Replogle (1976). However, under Reddell's scheme, an intermediate advance distance and time are recorded to provide additional data. A procedure is proposed to solve for k and a without any assumptions about the surface storage, but will require some more definite mathematical verification. In previous schemes proposed by Reddell (1981), the surface storage term was ignored completely. While this term is less significant for furrows than border, Katopodes has shown that this is, at least theoretically, infeasible. The importance of Reddell's work is that he is trying this on an operational

basis. His objectives are slightly different, since in theory he will be adjusting the stream size continually through the irrigation process, rather than trying to find a single optimum stream size. One possible solution to this would be to start with the maximum nonerosive stream size and gradually cut back to a stream size matching the final infiltration. The problem then is to determine exactly how to change the stream size.

Smith and Duke (1984) at Colorado State University experimented with real time sensors in furrows for measuring advance times. They used the data to estimate k and a with Elliot and Walker's (1980) two point method. The major problem with this approach is the estimation of surface storage, which can be inaccurate. As noted by Katopodes, this can lead to significant errors in parameter estimations. The results of Smith and Duke's studies indicated that spatial variation in parameters and nonuniform advance can cause serious problems in the estimation process. Variations in surface storage could have contributed to some of these estimation problems. Clearly there is room for much work in this area.

Elliot and Eisenhauer (1983) compiled a list of methods that have been proposed for finding furrow infiltration from a volume balance. Unfortunately, many of these methods are based on post-irrigation analysis, while the emphasis here is on real time analysis.

Weir (1984) from New Zealand has also worked on the inverse or identification problem. His work would apply mainly to cracking soil which exhibit high infiltration followed by a final infiltration rate. His infiltration function is of the form

$$Z = b + ct \tag{5}$$

which is identical to Eq. (4) after t_c. However, at short times during advance, this function is not particularly applicable. He has reported problems associated with irregular bottom slopes which cause advance to be highly nonuniform and unpredictable. These problems are similar to those reported by Smith and Duke. Solutions presented by Weir for the inverse problem have some theoretical significance, but may not be general enough for practical use.

From the foregoing discussion, there appear to be a wide variety of possibilities for the estimation problem. The key to solving this problem may be in the use of all available information. With information from previous irrigation, from previous sets for the current irrigation and from the current irrigation on the current set, it may be possible to make some realistic predictions on infiltration and roughness, from which good recommendations on stream size and cutoff time can be made. Spatial nonuniformities in parameters will cause some difficulties, but techniques are available that may help minimize these problems. For example, Baysian statistics could be used to determine new estimates of parameters from data on the current irrigation plus prior estimates of what these parameter values are expected to be. Such a problem also

suggests the use of artificial intelligence to evaluate conflicting information and provide recommended values of these parameters with confidence bands. Optimum operational settings could then be developed for a range of values rather than a single set of values as discussed for design. This is a difficult problem that will take some innovative thinking for its solution.

PROCESS CONTROL PERSPECTIVE OF IDENTIFICATION/OPTIMIZATION

There are many tools available in process control which may shed some light on this problem. Thus it may be advantageous to describe the problem from a strictly control system's perspective. The important features of a control system for a process are observability and controllability, that is, "Is the process observable?" and "Is the process controllable?" Inputs to the process can be controllable inputs or uncontrolled inputs. The stream size and cutoff time are usually controllable inputs. The infiltration and roughness are uncontrolled inputs to the process. The state of the process is described by fixed state parameters (e.g., slope, field length and end conditions) and state variables (e.g., flow depth and discharge at various locations along the border). There are two types of output; the useful (desired) output which in this case would be the distribution of water (i.e., water stored in root zone, deep percolation and runoff), and other incidental output. In this problem, the uncontrolled inputs are not known and the controllable part of the process is completed prior to the useful output.

Such a process is neither observable nor controllable as stated above. The problem here is to improve the observability of the process and make it controllable. One scheme to improve controllability is through the use of mathematical relationships between all input parameter values and the useful output. These relationships can be developed on a case by case basis with existing theory and models, but are not now available in general. This requires, however that values for the unobservable input be somehow estimated. Several approaches to making the system observable have been suggested in previous sections. One is to make some physical measurements prior to the process. However, this is not always reliable. Another is to estimate these variables from previous observations of the process. However, the unobservable, and sometimes the observable, input variables are continually changing. Another would be to use the incidental input about the state of the system (e.g., advance distances and flow depths) to estimate the unobservable input. This is basically the identification or inverse problem. Artificial intelligence appears to have some application in this identification process.

Another approach to minimizing the time delay effects is to observe similar processes which occur just prior to the process to be controlled, where changes in the unobservable input variables are expected to deviate similarly from previous estimates (i.e., other borders in the same field). These other processes would have slightly different state parameters and different estimates of the unobservable input. The adjustments would come from observations of opportunity times and runoff

volumes, not from estimates of infiltration. This approach would follow similar lines to that suggested by Merriam (1978). Without exact knowledge of infiltration and roughness, some empirical rules would have to be developed to determine appropriate adjustment. This suggests the use of an expert system approach.

SUMMARY

Border irrigation is a complex physical problem which is difficult to control precisely. The biggest problems in control is the inability of current procedures to reliably estimate infiltration prior to the irrigation event. Estimates of infiltration from measurements made during advance are complicated by unknown roughness effects. For control, the problem is to find the optimum stream size and time combination. In design, the problem is to design such that high efficiencies an be obtained for a range of infiltration (as well as roughness and management allowed deficit) conditions with little adjustment in stream size. New approaches are presented which attempt to solve these problems. Together, these approaches could result in considerable improvements in border strip irrigation efficiencies.

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PERSONNEL

A. J. Clemmens

Table 1. Computed advance distances for various infiltration functions with zero-inertia border-irrigation model

Conditions	Basin 7	Basin 8	Basin 2
Observed	finished[a]	to 250 m $\pm$ 5 m	to 260 m $\pm$ 5 m
Computed infiltration functions			
Power function from rate data	finished	to 252 m	to 256 m
Branch function with i_f = 0.508 cm/h	finished	to 274 m	to 278 m
Branch function with i_f = 0.762 cm/h	finished	finished	finished
Power function from cumulative data	finished	finished	finished
Intake Families			
SCS 1.0 (in/h)	finished	finished	finished
SCS 1.5 (in/h)	finished	finished	finished

[a] Indicates that irrigation stream advanced to the end of the basin.

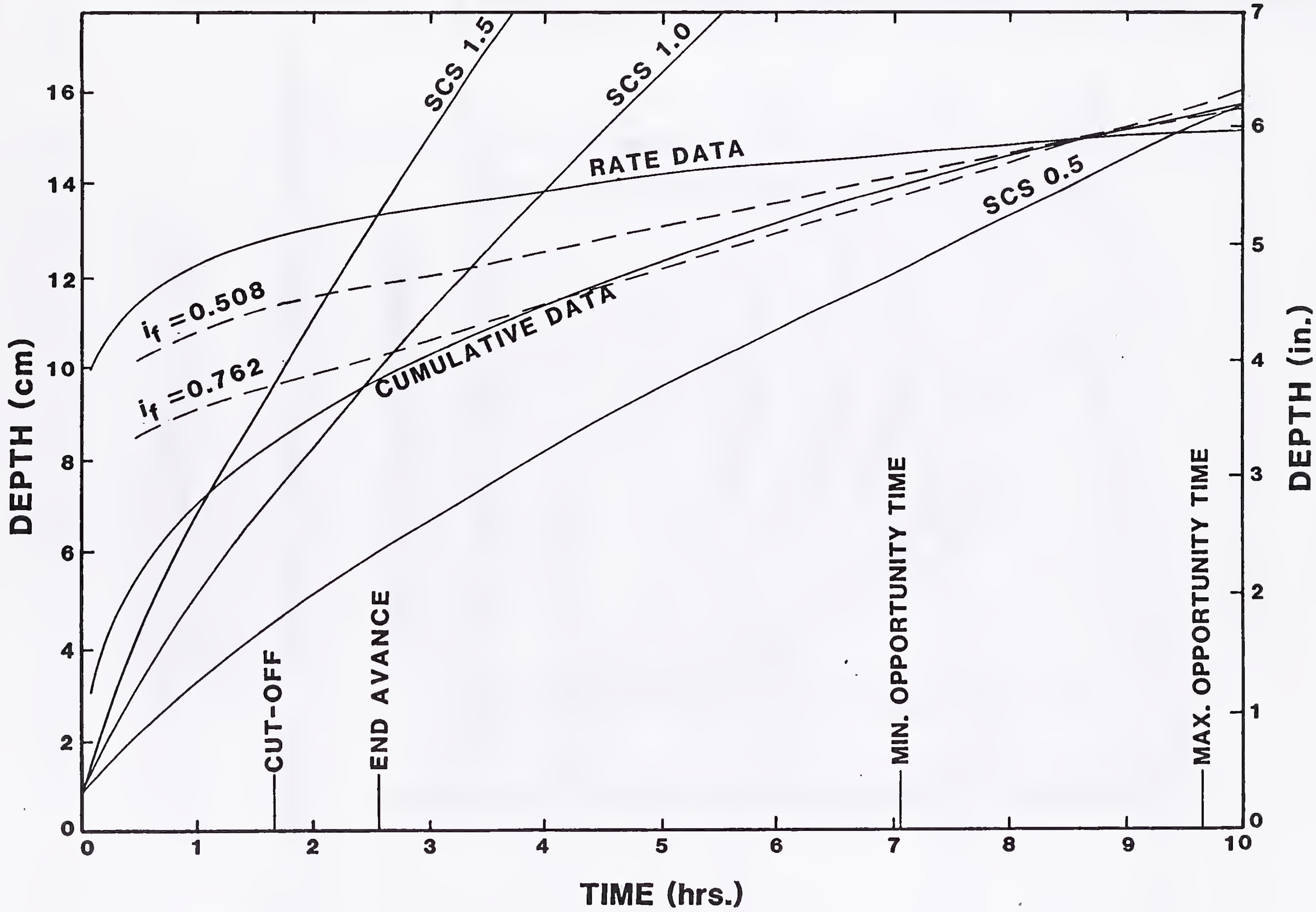

Figure 1. Cumulative infiltration for basin number 7 on the Wise Farm, Wellton, AZ, 20 February, 1979. Curves represent three SCS intake family functions and four functions representing results of ring infiltration analysis.

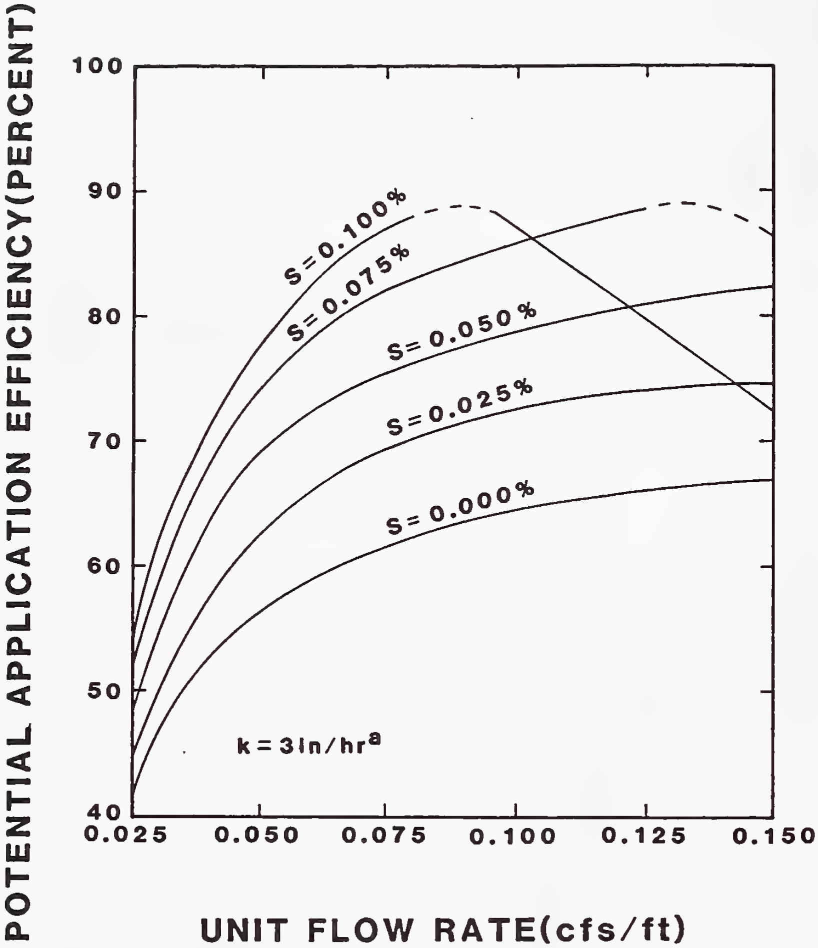

Figure 2. Potential efficiencies for first set of conditions;

field length = 600 ft.
Manning n = 0.15
Management allowed deficit = 3 in.
Kostiakov K = 3 in/hr^a
Kostiakov a = 0.6

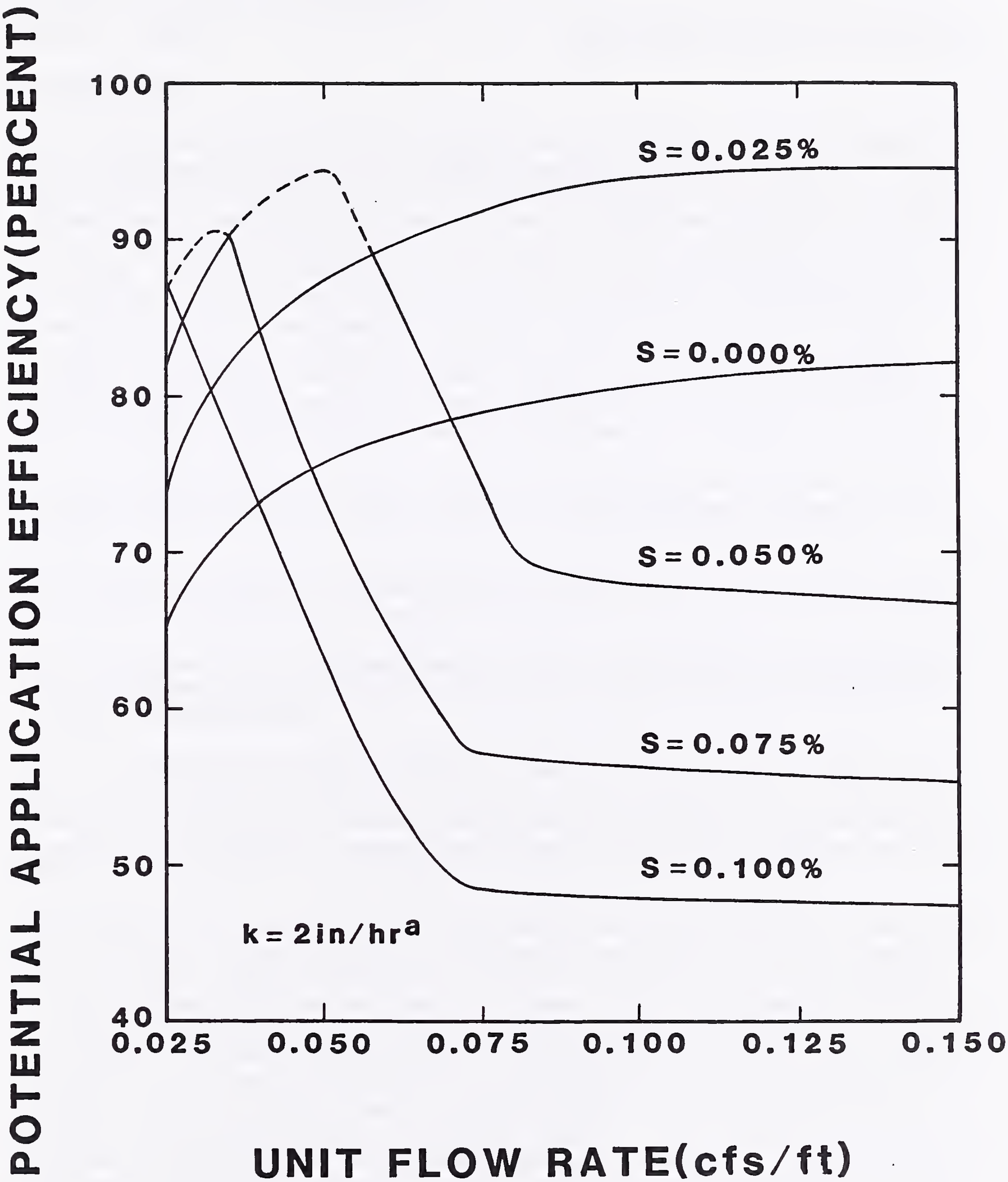

Figure 3. Potential efficiencies for second set of conditions; as before but with Kostiakov K = 2 in/hr^a

TITLE: CANAL SYSTEM OPERATIONS

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION

The operation of canal systems delivering irrigation water to farmers can significantly affect the farmers' ability to apply water uniformly, efficiently, and flexibly. For farmers to effectively respond to market adjustments (requiring a change in cropping patterns) or the development of new agricultural practices, they need a water supply that is flexible in terms of delivery frequency, rate, and duration. However, actual frequencies, rates, and durations are constrained by the delivery system's physical and managerial structure, and these constraints often reduce the farmers' management options. Operation of existing canal systems indicates a conflict between easy to manage delivery schemes, and flexibility for the water user. Efforts to investigate and resolve this conflict reveal certain specific problems:

1) The relationship between a canal system's physical and managerial configuration, and the farmers' delivery and management options is not well-understood, nor has there been much research in this area;

2) Instrumentation for monitoring canal operations at a detailed level has not been available at reasonable cost;

3) Canal capacities (an important factor in the cost of constructing canal systems) required for flexible water use by farmers, have not been adequately researched;

4) The response of canal structures (gates, weirs, and the like) to non-steady flow conditions has received little attention in the literature. Present in-canal structures for maintaining constant levels or flowrate are limited by non-adjustability, inaccuracy, or power requirements that translate into higher cost and lower reliability.

The objectives of the canal system operations research project are threefold, with the overall intent of improving water deliveries. First, we seek a better understanding of the effect of delivery system operating conditions and policies on farm operations. System parameters such as delivery schedules, lead time for ordering water, restrictions on changing flow rates and duration, and non-uniformities in flow may all limit a farmer's management options, and these constraints need to be quantified. Second, we seek a better understanding of canal operations in general, and their effect on farm deliveries. This involves studying various control schemes, structures, and canal capacities with an eye to allowing a delivery agency to provide better service economically and with ease of management. Third, we seek to resolve the present conflict between easy to manage delivery schemes and flexible water use by farmers, through the development of improved operational schemes and associated control structures.

Specific research approaches that have been initiated and proposed for achieving the project objectives follow.

1) Detailed monitoring of lateral canals has begun in the Wellton-Mohawk Irrigation and Drainage District and the Imperial Irrigation District. Inflows, outflows, and water levels are being precisely measured to provide a data base from which the effects of system management and structures on flow transients and delivery uniformities can be studied.

2) Development continues on improved, accurate and adjustable canal control structures for maintaining constant flow rates within a system. The Dual-Acting Controlled Leak (DACL) mechanism is being tested further, and design considerations are being evaluated.

3) Improved canal system control schemes are being approached through studies of responses at flow furcations to non-steady conditions and transients, dynamic regulation with local controllers, and by canal modeling.

WELLTON PROJECT

The Wellton-Mohawk Irrigation and Drainage District (WMIDD), located along the Gila River east of Yuma in southwestern Arizona, provides water to about 60,000 acres of farmland. Water is ordered with three days' notice for any duration and standard deliveries of 15 cfs (with 20 to 25 cfs more common), and ditchriders are on 24 hour call. A cooperative agreement was reached with the WMIDD to study canal operations, principally through the detailed monitoring of flow along two lateral canals, one near the upstream end of the district (WM17.0) where main canal levels and flow should be reasonably stable, and the other near the downstream end (M42.9) where main canal flows vary widely. Our intent is to compare actual and ordered deliveries, identify non-uniformities in flow and trace them to their sources, determine the contributions of delivery policies, control structures, and location within the ditrict to non-uniformities, and to draw conclusions about their effects on farmers' management options and water use efficiencies.

In 1985, instrumentation was installed along a three-mile length of the upstream WM17.0 lateral, from the main canal offtake to the point below which typically only a single farm delivery occurs at one time. Inflows, outflows, and water levels are measured at each lateral check structure and farm turnout, which amounts to 17 levels and 9 flowrates measured at 13 instrument sites (see Table 1). To economically measure several water levels in close proximity, we employed a multi-channel data logging system (Easy Logger by Omnidata International, Inc.) coupled to double-bubbler/pressure transducer mechanisms (Dedrick and Clemmens, 1985). At a cost of between 600 and 700 dollars per level or flowrate measured, this system is far less expensive than commercially available devices costing more than 1000 dollars per level or rate measured. Installation took place during April, May and June of 1985 and consisted of: mounting hardware in weatherproof boxes that were

attached to district control structures and painted white to reduce temperatures inside to near-ambient; constructing four concrete measuring flumes at sites that did not previously have them; and plumbing plastic tubing encased in PVC pipe for the bubbler lines.

Measurements are taken every 15 minutes by the data logger and recorded on a detachable EPROM device. Replacement of filled EPROMs and batteries requires an on-site visit approximately every three weeks. At the U.S. Water Conservation Laboratory, data are transferred from the EPROMs through a microcomputer to files on the Lab's minicomputer. EPROMs are then erased for reuse; batteries are also recharged to be used again. Table 2 contains a listing of the program elements for setting up the Easy Logger.

Although the equipment was installed in the spring, system evaluation continued throughout the year with a number of problems becoming apparent. In September, for example, several of the pumps supplying air to the bubblers failed due to too long a piston stroke, and all were replaced with a different model supplied at no cost by the manufacturer. Also in September, due to greater than expected power consumption, the loggers' internal battery configuration (8 D-cells, non-rechargeable) was abandoned in favor of two external, rechargeable 6 volt batteries, which made replacement easier and eliminated the cost of the D-cells. Canal cleaning operations and brush-burning along the canal banks have from time to time required repair of bubbler tubes, and lightening strikes and other unknown causes have occasionally required reprogramming of the logger units. Overall, however, the system has performed as expected and has provided a rigorous field test of the double-bubbler/pressure transducer mechanism and the remote data logging system. The lateral will remain instrumented through 1986 and hopefully our experience in operating the equipment will provide a more complete data set than in 1985.

Further plans for 1986 are to similarly instrument the second, downstream lateral. In addition to being located where levels in the main canal fluctuate more, this lateral differs from the first by being longer and having a large sublateral canal. This lateral has a design capacity of 90 cfs at the offtake from the main, compared to 60 cfs for the upstream lateral. Approximately 23 water levels, 14 gates, and 24 flowrates will be monitored (see Table 3). Also in 1986, analysis of lateral operations will begin in earnest, starting with organization of the data into a relational database, development of rules for identifying and tracing non-uniformities, and comparison to district delivery records. Ultimately, this analysis will be tied into the work being conducted on dynamic regulation and canal modeling.

IMPERIAL PROJECT

Located across the Colorado River from WMIDD, in southeastern California, is the Imperial Irrigation District (IID) which provides water to 500,000 acres of farmland in the Imperial Valley. Water is ordered from IID with three days notice for 24 hour durations, standard

deliveries of 11 cfs, and the ditchriders work 8 hour shifts. A monitoring project similar to that in WMIDD has been initiated in IID, to contrast the differences in scale and operating procedures. Fortunately, our project needs dovetail very well with an ongoing IID conservation project aimed at reducing tailwater losses. In fact, due to an excellent cooperative relationship with IID, it appears that our principal responsibility will be data analysis, while IID will install the monitoring equipment and perform most of the data collection duties.

We have surveyed four eight-mile long laterals with offtakes from the East Highline main canal for this project. The laterals were selected based on their position relative to a check structure on the main canal, and because two are fully lined, and the other two only partially lined. As with WMIDD, inflows, outflows, and water levels will be measured at each check structure and farm offtake. Measurements will be made every 15 minutes using the Easy Logger data logging system, coupled here with float operated potentiometers, instead of bubblers. Data will be stored on detachable EPROM devices that will be collected every few weeks, then transferred to computer. We plan then to physically transfer the data to U. S. Water Conservation Laboratory computer facilities via streamer tape. It is expected that Lab personnel will assist in gathering the EPROMs from the field. The monitoring equipment will be installed in early 1986, and will involve constructing more than 100 measuring flumes, stilling wells to house the floats at each measuring site, placing the logging devices, and running electrical cable from the loggers to sites in close proximity. Data collection should begin shortly after installation is complete. Although we have met with IID personnel several times to plan installations and data requirements, IID will be shouldering the entire cost of installation. In return, we will be coordinating our analysis of the data closely with IID's needs.

In 1986, the major thrust of our efforts will be the development of analysis techniques, identification and quanitification of non-uniformies in lateral and on-farm flows, and comparison to conventional district records of flow rates and volumes. In concert with the analysis of flows in WMIDD, we hope to draw conclusions about the effects of different delivery policies and structures on farm operations.

DUAL-ACTING CONTROLLED LEAK (DACL) CONTROL SCHEME

The basic concept and mechanism for the DACL control scheme have been written up in manuscript form. The following simply provides a discussion of control variables and a design example.

Control response: There are three factors which affect the control band for the dual-acting controller. First, the pressure on the supply valve causes its float to change buoyancy, thereby changing the valve response curve. This can be controlled by the design of the valve floats and movement arms. Second, the float chamber level will cause a slight change in pressure on the valves. This can be somewhat controlled by larger diameter gate floats (giving less water level change to reverse gate friction) and by reducing gate float travel relative to gate travel

(i.e., providing leverage). And third, some overshoot could be experienced if the canal travel time from the gate to the flume and the rate of gate opening are such that the gate opens slightly too much. For the installations tested here, this was not a significant factor in response.

In designing a dual-acting controlled leak system, the two main factors are response time and control band width. In some cases, these may be conflicting requirements. However, we have come up with the following design criteria which should prove satisfactory for most installations.

1) Channel travel time at full flow should cause less than 1% change in flow rate (e.g., at equilibrium leakage rate from one side).

2) Response time for half to full channel flow computed from maximum leakage rate (one direction) should be less than 20 minutes (effects control valve size).

3) Two times the gate friction should be provided by the gate float on either side of equilibrium for safety.

4) Friction reversal time computed at the maximum leakage rate (one direction) should be less than 10 minutes.

5) Available head and drain outlet level at all gate openings should be considered when locating the float positions vertically.

6) The control float size and float moment arm should a) limit effects of pressure to a 6 mm band, b) limit the friction reversal time for a 3 mm shift to under 30 minutes, and c) provide adjustments for 3 mm shift within 10 minutes after reversal.

This list of criteria is presented so that the major factors which control design of these systems will be considered, not that the exact values given above are followed.

Design Example: The following design example represents typical conditions for a lateral canal heading.

Given: A turnout from a main canal into a lateral canal with a 2.5 m^3/s (88 cfs) capacity. A radial gate 2.5 m wide, 2.5 m high with a 3 m radius is used to control the lateral flow. The lateral canal has a 0.60 m bottom width, 1.5 to 1 side slopes and is 1.2 m deep. A broad-crested weir is placed a distance L of 30 m downstream from the gate. The flow depth at maximum flow is 1.0 m, and at half flow is 0.80 m. The channel bottom drops 0.2 m at the gate structure. The head on the upstream side of the gate ranges from 1.8 to 2.3 m. Maximum gate friction is estimated to be 3.0 KN (670 lbs). The lifting force required to move the gate after friction is 6.5 KN (1460 lbs). It is assumed that the gate is to be open when the float chamber is empty.

Problem: Design a control mechanism to keep a constant discharge into the lateral canal.

Solution: Design of this type of system does not require exact dimensions on any of the components. The design steps are given below.

1) Compute the float and counterweight sizes. The float volume to overcome friction would be

$$3.0 \text{ KN} * (1 \text{ m}^3 \text{ water}/9.805 \text{ KN}) = 0.31 \text{ m}^3 \text{ of float}$$

The total float volume should be 4 times that necessary to overcome friction, since friction occurs in both directions and a 2 to one factor of safety is necessary. Thus the float volume is 1.24 m^3. The float must be heavy enough to sink completely into the water (at least 12.0 KN). At equilibrium, with no frictional forces applied, the float should sit midway in the water, resulting in a net force of 6.0 KN. Since the gate lifting force is 6.5 KN, only an additional 0.5 KN counterweight is needed, which can be added to the float weight, giving a combined float and counterweight of 1.24 m^3 and 12.5 KN. (Note that the required weight to volume ratio is almost the same as water implying that a tank filled with water could serve as the float).

2) Determine gate response. An approximate orifice equation is used to estimate gate response, namely

$$Q = C\ A\ (2gh)^{1/2}$$

where C is a discharge coefficient (0.61), g is the acceleration of gravity (9.81 m/s^2), h is the differential head on the orifice, A is the area of gate opening, and Q is discharge. At maximum flow and head, Q = 2.5 m^3/s, h = 2.3 + 0.2-1.0 = 1.5 m. Solving for A gives 0.755 m^2. For a gate width W of 2.5 m, the gate opening <u>a</u> would be 0.302 m since A = <u>a</u>W. A 1 mm change in gate opening would cause a (1/302)*100 = 0.33% change in flow.

At half flow, the gate opening would be 0.142 m. Here a 1 mm change in gate opening would cause a 0.71% change in flow. At full flow and a low head, the gate opening would be 0.370 m. These values will be used in later design steps.

3) Compute channel travel times.

Channel flow area A = 1.0 * (0.6+(1.0*1.5)) = 2.1 m^2
Channel velocity v = Q/A = 2.5/2.1 = 1.2 m/s
Channel travel time t_c = L/v = 30/1.2 = 25 sec.

4) Compute maximum rate of gate movement to eliminate overshooting of control. The travel time t_c should cause less than 1% change in discharge for gate movement at equilibrium leakage rate (one way). If 1 mm causes 0.33% change, 3 mm will cause 1% change. Three mm change in 25 seconds gives a maximum rate of gate movement of 7.2 mm/min at the one way equilibrium flow rate.

5) Compute minimum rate of gate movement to get desired response times. In order for the gate to travel from its position at full flow (0.302 m) to its position at half flow (0.142 m) or 160 mm in 20 minutes, the gate would have to travel at an average rate of 160/20 = 8 mm/min at roughly half way between the one way equilibrium flow rate and the maximum one way flow rate.

6) Estimate float dimensions from available float travel. At this point it will be assumed that the available head at the site is sufficient to drive the system. If this is not the case, other arrangements would have to be made such as disposing of drain water to a lower lying drainage canal or to a sump from which it can be pumped out. At the minimum canal head then, the gate must be able to go from a closed position to full open. Some driving force is necessary to provide flow through the control valves. A suggested minimum value is 0.15 m on either side. Gate travel at this low head is 0.37 m. The available head at the site at full flow and low head conditions is 1.0 m. The available head for frictional reversal is 1.0 - 0.37 - 2(0.15) = 0.33 m. Dividing this in two for friction in either direction, leaves only 0.165 m of height for a 0.31 m^3 volume. The required float area is then 0.31/0.165 = 1.88 m^2. A round float with a 1.55 m (5.08 ft) diameter would be large enough. If more than ample head is available, the float diameter can be made a more convenient size than computed here (i.e., larger).

7) Select float chamber size and compute leakage rate limits. A 1.6 m diameter float chamber could provide about 25 mm clearance around the float. If the gate and float are on a one-to-one basis for both force and travel distance, then the gate travel speed limitations computed above can be converted to leakage rate limitations. The limit for overshooting was 7.2 mm/min, which for a 1.6 m dia. float chamber would correspond to a maximum equilibrium leakage rate of 14.5 l/min. The limit for response rate was 8 mm/min, which corresponds to a minimum average leakage rate of 16.1 l/min (i.e., half way between one way maximum and equilibrium leakage rates).

A reasonable one way equilibrium leakage rate for this system would be 5 l/min. To meet the response time criteria for this system would require a maximum leakage rate of roughly 5+2(16) = 37 l/min. At one meter available head, the maximum valve flow rate for a 25.4 mm dia. valve should be on the order of 80 l/min (from orifice calculations). Due to large head losses, the available head was reduced for the tests we ran and the maximum leakage rate of 14 l/min at a 0.30 m head was recorded (it would calculate out to be about 43 l/min for the full available head). Thus some time after design of the entire system, these responses should be reviewed with the line head losses included. The 25 mm dia. valves are chosen here for design. In a similar sized installation, those 25 mm dia. valves were used with good success and reasonable response times. The reversal time is related to the annular area between the float and the float chamber walls. At 5 l/min leakage rate, a change of 0.33 m required, and an annular area of 0.124 m^2, the reversal time would be 8.2 min, which looks reasonable.

8) Select control float size. A 6 mm control band is desired for a 0.5 m upstream head change. Half the band is allowed from this head change, and the control is shifted by one half of the pressure change, thus 6 mm is used in the calculations. The float area can be found from

$$h_v A_v = h_f A_f R$$

where h is the head of water or float submergence, A is the area, R is the relative moment arm of the float and valve piston to the pivot point, and the subscripts v and f refer to the valve and float, respectively. At maximum head and flow, the head on the valve would be roughly 1.117 m (0.5+0.15+0.165+0.302). At minimum upstream head and maximum flow, the head would be 0.685 m (0.15+0.165+0.370). Solving the above equation for h_f for the two upstream heads (min and max) and taking the difference gives

$$dh_f = dh_v \; A_v/(A_f R) \qquad \text{or}$$

$$A_f > dh_v \; A_v/(dh_f \; R)$$

For our example, dh_v = 1.117-0.685 = 0.432 m, dh_f = 0.006 m, A_v = 0.00049 m^2, and R = 10 as an initial guess. This gives A_f = 0.0035 m^2 or a 67 mm (2.6 in) dia. float.

The total float volume must be capable of resisting the maximum pressure or

$$V_f > h_v A_v/R \quad \text{or} \; V_f > 0.00023 \; m^3$$

A 67 mm dia. spherical float has a volume of 0.000157 m^3 which is not enough. While a 76 mm dia. float would be large enough, some margin of safety is needed and the response criteria require a given diameter at the water level. An 87 mm dia. spherical float would be needed to resist maximum force at 2/3 the volume. The 93 mm dia. floats used in prior tests proved satisfactory.

9) Check moment arm response. The moment arm response is determined by computing the changes in control valve opening for changes in upstream pressure. Thus estimates of control valve positions and opening areas are needed. It is assumed that the valve plunger represents a situation similar to a rectangular sluice gate on a circular pipe opening. Tables for area in a circular section as a function of depth are available from several sources.

Using an orifice equation with Q = 5 l/min, and h = 1.117 m, gives A = 29.2 mm^2. For a diameter of d = 25 mm, A/d^2 = 0.047. From circular area table, the relative opening $\underline{a}/d$ would be about 0.110 making $\underline{a}$ = 2.75 mm. If the level were to change 3 mm, the valve would shift 0.3 mm (10:1 moment arm), making the opening 3.05 mm, $\underline{a}/d$ = 0.122, A/d^2 = 0.0547, A = 34.2 mm^2, and Q = 5.86 l/min. The other valve would reduce flow a similar amount with Q = 4.25 l/min. The net change in Q is 5.86 -4.25 = 1.61 l/min. Reversal requires a total volume of 0.124 m^2 times

0.33 m, which at 1.61 l/min would take 25.4 min, which looks reasonable. A shorter moment arm would reduce this reversal time requirement, but would increase the float size necessary to limit the control band.

A 3 mm error in level would represent about 1% change in flow. At maximum head and flow, this would require a 3 mm change in gate setting. At one half of the 1.61 l/min change in net leakage rate, a 3 mm change in float chamber volume ($A = 2.01\ m^2$) would require 7.5 min, again a reasonable time.

At lower heads and lower discharges, these response times and control bands will vary. Further checking of these responses for different conditions is advisable.

Future plans: For 1986, we plan on installing a DACL system on the outlet of two reservoirs, one at the MAC farm for a yield/uniformity research study, and one on Ralph Wong's farm near Tucson. These two systems will utilize a recently developed neutral acting, clog free valve for pipe outlets, which has not been reported elsewhere. It is hoped that after studying the lateral canals in the IID system that a DACL system will be installed on one of these lateral headings. We have also discussed converting the Danaidean system at the Wellton canal heading to a DACL controller with the WMIDD. Future installations depend on cooperators.

Summary: The DACL system has proven to be an excellent control device for maintaining canal water level downstream from a control structure. For the configurations studied the level was controlled to within a 6 mm band or roughly $\pm$ 3 mm. This level of control, which has not been available on previous control devices, is possible under the worst operating conditions e.g. high debris and sediment loads, and fluctuating upstream levels. Since the control of flow rates requires more precise control than control of just water levels, the DACL system is particularly suitable for constant flow rate control. The DACL system is also usable for upstream control and has more configuration options than previous controlled leak systems. It also has advantages over electrically controlled motorized gates which require power. The major factors which affect the response times and control bands have been identified and basic design criteria have been presented. The DACL system has not been tested under actual operating conditions.

CANAL CONTROL SCHEMES

Furcation Flexibility: Critical to the operation and modeling of canal systems is the accurate measurement of flow rates and the hydraulic heads that drive a system. Inaccurate estimates of flow may result from measurement errors or from the presence of transients or actual changes in flow rate at the structure where measurements are made. One measurement of this error is the sensitivity, S, of a structure to inaccurate measurement, thus

$$S = \Delta Q/Q = u\ \Delta h/h$$

where u is indicative of the structure type, and Δh may refer to head reading error, misplaced gauging station, an actual unnoticed change in water level, etc. Accurate measurement of head becomes more critical for a given structure at low heads, and is more critical for structures with relatively large sensitivities.

Structure sensitivities are especially important quantities when looking at what happens at a canal branching, or furcation, when changes in incoming flowrate are introduced. How an error in flow measurement of an actual change in flowrate is divided among the branching canals depends on the sensitivities of the structures that divide the flow. A common situation involves a bifurcation with an offtake canal structure and a check structure in the continuing supply canal. To describe the division of a change in flow, ΔQ, at a bifurcation the term flexibility, F, is defined as the ratio of the offtake structure sensitivity to the continuing supply check structure sensitivity

$$F = \frac{S_o}{S_s} = \frac{\Delta Q_o/Q_o}{\Delta Q_s/Q_s}$$

where $\Delta Q_o + \Delta Q_s = \Delta Q$, and $Q_o + Q_s = Q$.

Furcation flexibility can be important in canal system management for distributing flow errors and transients throughout a system in specific ways. For instance, a bifurcation with $F = 1$ will divide ΔQ into equal proportions of Q_o and Q_s, and error will be evenly distributed through the system. If $F < 1$, ΔQ_o will be proportionally smaller than ΔQ_s and most of ΔQ will remain in the continuing supply channel, a situation that may be desirable where very accurate offtake deliveries are required. Consequently, however, errors in flow will accumulate toward the end of the supply canal which may result in wasting water. A bifurcation with $F > 1$, with flow error mostly shunted through the offtake structure may be desirable where there is risk of overtopping the supply canal, or toward the end of a system where variable offtake flows can be tolerated and/or excess supply cannot be wasted or drained away.

Analysis of flexibility has the potential to be an important tool in examining the operation of existing canal systems, and in the planning and design of new control schemes and structural configurations. To this end we are developing a computer program to calculate flexibilities for all combinations of flow control structures common to irrigation canal systems, and various flow types (e.g., orifice outlets submerged or free-flowing). The program will allow the user to see the response at an existing furcation to flow errors or transients introduced by present operating conditions, to simulate the effects of alternate operations, or to experiment with the selection of structures and conditions for the design of new or renovated system. It is expected that this program will also have use as a component of large-scale canal network models.

In 1986 we plan to complete the writing of the computer program. One foreseen difficulty is expressing "flexibility" where a furcation divides flow into more than two portions, for instance, two farm offtakes and a continuing supply canal. Because flexibility as currently defined applies only to bifurcations, we are attempting to develop a more general term, coined the responsiveness of a single structure, to describe the division of incremental flow changes introduced into furcations of two or more structures. Responsiveness, R, is defined for a given structure at a furcation as the ratio of the change in flow at that structure divided by its original flow, to the total change in flow divided by the total original flow incoming to the furcation,

$$R_k = (\Delta Q_k/Q_k)/(\sum_{i=1}^{n}\Delta Q_i/\sum_{i=1}^{n}Q_i)$$

The physical significance of various values of R (e.g., R_k equal to, less than, or greater than one) has yet to be determined. It may be that an alternative derivation would be preferable, such as

$$R_k = (\Delta Q_k/Q_k)/(\sum_{\substack{i=1\\i\neq k}}^{n}\Delta Q_i/\sum_{\substack{i=1\\i\neq k}}^{n}Q_i)$$

at a furcation with n structures, which for two structures is identical to bifurcation flexibility.

Canal modeling: In order to study the impact of canal controls on the flow of water in canals, it will be necessary to model canal hydraulics. Several canal hydraulic models are available, however from secondhand knowledge, they appear to be very complex and costly to run. Such a model was developed by Amorocho and Strelkoff in the 1960's and was used by Zimbelman in the late 1970's. This model uses the method of characteristics and the full hydrodynamic equations of continuity and momentum. Research on irrigation flow has produced models that are based on zero inertia and may be adaptable to canals. Such models are much more efficient for canal reaches. In the earlier models, flow through gates was modeled exactly. For our use, we could use simple head discharge relations for these gates.

Another model is available through the U. S. Bureau of Reclamation. One computer program, GSM (Gate Stroking Model), is used to develop steady state conditions. A second program, USM (UnSteady Model), is used to model unsteady flow in the canal. We have not looked into this model and so we do not know how the computations of flow through the reach are made, how the in-line gate discharges are determined, and how the offtake heads are determined. For our research, it is important that the offtake discharges can be modeled in some way as well as in line flows. We may even want to be able to express this strictly in terms of structure flexibility to flow changes, rather than exact hydraulics. The USBR model is fairly costly to run, so we suspect it is based on earlier canal modeling work.

We have discussed the development of a canal network model. A network model was developed at the U. of Illinois for open channel sewers. We suspect that this model would not be capable of handling the control structures in the way we need them handled, if they have any structures at all. We might be able to learn a considerable amount from their approach. Other work on canal sewer models was done at Colorado State U. by Dennis Morrow, but we're not sure how this applies to our needs.

It is likely that we will be forced to do some model development in order to study the nature of control and the effects of travel lag time. Some work on response curves for travel lag time were developed by Tamai and Iwasaki from the University of Tokyo, Japan. They attempted to use dimensionless variables to develop response time curves which could be used for any canal. This has a lot of promise and should be pursued.

Local Controllers for Dynamic Regulation: Dynamic regulation is a concept for allowing demand operation for a large canal, that is users could take water from this canal on demand. A feasible scenario would be for demand at the lateral heading and arranged systems within the lateral canals themselves. The schemes proposed here would probably not be capable of handling large diurnal fluctuations in flow (e.g., no night time irrigations). Dynamic regulation as currently defined requires extensive engineering analysis of canal and structure hydraulics so that accurate flow rates and responses can be modelled.

Two examples of dynamic regulation are the Canal de Provance in France which is predominately predictable M & I and residential use, and the scheme proposed by Clemmens in 1979. The basic premise of dynamic regulation is that some canal storage is available to handle short fluctuations in demand. Under the Canal de Provance system, the central control system responds to changes in demand and adjusts in-line canal gates to adjust flow continuously. The approach by Clemmens assumes more storage and less real time adjustments (e.g., daily).

A major consideration for this approach is the effect of these changes in storage and water levels on flow fluctuations to the lateral canals. Of course, automatic flow rate controllers (local or remote) could be implemented to minimize this consideration. I assume that the Canal de Provance regulates offtake flow remotely from a central location. Under Clemmens' scheme, part of the control algorithm attempted to limit offtake flow variations to less then 10%.

A new approach is needed to implement this type of scheme without extensive remote monitoring and without large amounts of canal storage. If dynamic regulation could be implemented primarily with local controllers, it may have a possibility of more widespread use. In some ways, dynamic regulation attempts to start with flow rate control at the canal heading, which reverts to upstream control immediately downstream, and progresses to complete downstream control at the lower end of the canal.

Current approaches use remote monitoring to feed back downstream conditions to adjust what are effectively upstream controls. Now, how can this be done primarily with local controllers?

Burt at Cal. Poly. is attempting to develop a feed back system for downstream control on steeply sloping canals with local controllers, when control of the supply is available. This has some strong possibilities. Under dynamic regulation as used here, less control of the supply is available than assumed by Burt. His scheme uses a series of water level measurements to project conditions of the downstream pool, similar to other schemes presented earlier.

In this new control scheme, local controllers would literally start as upstream controllers at the head of the canal and progress to downstream controllers at the downstream end. The concept is to spread the difference between outflows and inflows (error) over the entire canal. Each local controller would monitor levels both upstream and downstream. The gate would be adjusted according the how far these levels were from some target levels. For the upstream end of the canal, more weight would be given to errors in the upstream water level than that given to errors in the downstream level. This weighting would gradually change such that at the downstream end of the canal, almost all weight would be given to downstream level errors. Since both upstream and downstream levels can vary from the target levels (e.g., both levels above target levels), some means of monitoring these errors periodically and adjusting the inflow rate would be necessary. This is meant to be a much looser control of canal inflow that downstream control.

None of the details on how to establish error weights and where to monitor water levels has been evaluated. It may also be necessary to have remote setting of the target water levels to account for changes in flow conditions and settings. It is hoped that methods could be developed to establish this scheme without extensive canal hydraulics studies. The research on modeling of canal hydraulic controls and travel lag transients may aid in this development.

Selecting canal control stuctures: Some of the basic control schemes and philosophy of control are reported in published papers. Table 4 is provided as a guide to the type of control devices which can be applied to structures in different parts of the canal network.

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PERSONNEL

J. D. Palmer, A. J. Clemmens, J. A. Replogle, A. R. Dedrick, R. Kapfer, J. Padilla, R. J. Gerard.

Table 1. Summary of locations within the Wellton Mohawk 17.0 lateral where water surface monitoring is required. Sites are identified according to farm deliveries or check gates.

Farm Delivery or Canal Check Gate Identifi-ation	Upstream Water Surface	Canal Check Gates	Downstream Water Surface or Weir	Field Delivery Flume or Weir	Total
Wellton heading	1	0	0	0	1
0.6 CK	1	3[a]	2	1	7
0.9 R	1	2	0	1	4
0.1 L	1	2	0	1	4
1.2 L	1	0	0	1	2
1.4 L	1	2	1	1	5
1.9 L	1	0	0	1	2
2.1 CK	1	1	0	0	2
2.4 L	1	0	0	1	2
2.6 CK	1	1	1	0	3
2.9	1	0	0	1	2
3.0 CK	1	1	1	0	3
3.0 L	0	0	0	1	1
TOTAL	12	12	5	9	38

[a] One of three bubblers recording water level for constant head orifice.

Table 2. Listing of program element values for Easy Logger data logging unit.

Setup Number	Description	Value
10	Set Location	Instrument Site Name
11	Set Operator	Optional
12	Set Sensors	
	Sensor	MSW
	Full Scale Range	100mV DC
	Sensor Formula	V
13	Set Wiring	
	Channel Number	26
	Sensor	MSW
	Channel Name	ATM
	Channel Number	26
	Sensor	MSW
	Channel Name	V1
	Channel Number	26
	Sensor	MSW
	Channel Name	V2
	.	
	.	
	... up	to V8, depending on number of measurements per site.
14	Set Scan Time	
	Scan Interval	15
15	Set Reports	
	Report Number	1
	Start When?	blank
	Stop When?	blank
	Report Interval	15
	R1C1 1st Heading	Slope
	R1C1 2nd Heading	blank
	R1C1 Units	mV/ft
	R1C1 Source	B
	R1C1 Type	Inst
	R1C1 Decimal	2
	R1C2 1st Heading	Offset
	R1C2 2nd Heading	blank
	R1C2 Units	mV
	R1C2 Source	Atm
	R1C2 Type	Inst
	R1C2 Decimal	2
	Remaining report columns (up to a total of 10) headings, units, sources, types, and decimal places expressed depend on specific information for a given site (e.g., level or flowrate measured, bubbler corrections, flume formulas, etc.).	

Table 2. (Continued)

22	Set Functions	
	Function 1	$B=(V1-V2)/\Delta H$
		ΔH is site specific
	Function 2	$Head(V,O)=(V-ATM)/B+O$
	Function 3	$Q(V,O,I,C,E)=$
		$I*(((V-ATM)/B+O)+C)^{E}$
23	Set Delays	
	Relay Digital	blank
	Relay Warm-up	30
	ATM Digital	blank
	ATM Delay	300
	ATM Avg Time	5000
	V1 Digital	A
	V1 Delay	30
	V1 Avg Time	5000
	V2 Digital	B
	V2 Delay	30
	V2 Avg Time	5000
	V3 Digital	AB
	V3 Delay	30
	V3 Avg Time	5000
	All other delays and average times are 30 and 5000, respectively.	
	V5 Digital	AC
	V6 Digital	BC
	V7 Digital	ABC
	V8 Digital	D
24	Set Comm Prot	
	Baud Rate	4800
	Parity	Even
	Duplex	Half
	Data Bits	8
	Lines Per Page	0
	Character Delay	0
	Line Delay	0
	Abort Character	27
	Pause Character	19
	Forward Space	32
	Line Width	100
	EOF Sequence 1st	26
	EOF Sequence 2nd	0
	EOL Sequence 1st	13
	EOL Sequence 2nd	10
	EOP Sequence 1st	12
	EOP Sequence 2nd	0
	Auto Print	On
25	Set Var Excit	
	Variable Excit	80

Table 3. Summary of locations within the Mohawk 42.9 lateral where water surface monitoring is required. Sites are identified according to farm deliveries or check gates.

Farm Delivery Canal Check Gate Identification	Upstream Water Surface	Canal Check Gates	Downstream Water Surface or Weir	Field Delivery Flume or Weir	Total
Heading	1	0	1	0	2
0.3	1	2	0	3	6
1.2	1	2	1	2	6
1.3R	1	0	0	1	2
1.5L	1	0	0	1	2
1.6L	1	0	1	2	4
1.8	1	2	1	2	6
2.1/2.2	2	2	0	2	6
2.1Lat-0.7	1	1	1	1	4
2.1Lat-0.9	1	1	1	2	5
2.1Lat-1.2	1	1	1	2	5
2.7R	1	0	0	1	2
2.9Lat	1	2	1	1	5
3.4	1	1	2	2	6
TOTAL	15	14	10	22	61

Table 4. Control schemes which are appropriate for different structures in a canal network.

	Manual		Automatic		Heading		In-line	
control	L	R	L	R	M	L	M	L
upstream	X	X	X				X	X
downstream			X	X	X	X	X	X
flow rate		X	X	X	X	X		
controlled volume				X	~~X~~	~~X~~	X	X
dynamic regulation				X			X	

L - local
R - remote
M - main canal
L - lateral and tertiary canals

TITLE: LONG-THROATED FLUMES AND BROAD-CRESTED WEIRS

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION

The theoretically related long-throated flumes and broad-crested weirs, which differ only in the location of the contraction in the flume throat, are experiencing increasing acceptance and use. The book, Flow Measuring Flumes for Open Channel Systems, (Bos, Replogle, and Clemmens, 1984), was available in late 1984 and throughout 1985 and will soon be available in Spanish edition. Many consulting firms and most water-interested state and federal agencies now are using it to design flumes for open-channel measurements. The weir style is the most easily applied to existing lined irrigation canals.

PROGRESS

Design

Two papers on design entitled "Contraction Ratios for Weir and FLume Designs" (Clemmens, Bos, Replogle) and "Design of Flumes and Weirs for Flow Measurement" (Bos, Clemmens, Replogle) were prepared. Most flume designs including those in the book mentioned above have had to depend on choosing amoung a limited, though large, selection of previously calibrated or computer-rated flumes with applications under a particular range of conditions. Flume designs outside of these ranges and selections were best developed by those with extensive experience and training. Frequently the appropriate range of application for a particular flume was not well understood by the designer and selections were made with inadequate regard to the channel conditions in which they were placed. This has resulted in several misinstallations of measuring devices and hinders the acceptance of flow measurement as a management tool in irrigation and other water resources applications.

The papers attempt to simplify proper design selections and give due regard to channel conditions. The previously developed computer model that served to generate the selection designs in the book was again used to develop a basic selection chart where an area ratio is used to prescribe or determine the approach channel Froude Number. The chart is applicable for rapid selection of rectangular and triangular flumes or broad-crested weirs for any channel. The first paper concentrates on development of the method and the second on its application.

In general the design procedure is an iterative process, with a number of trials before a final design is selected. The procedure may appear complex, but the various iterations converge rapidly. The only difficult part of the process is estimating flow conditions prior to placement of the structure. In existing systems, good field observations will eliminate this.

Large Flumes

Corrections to the Salt River Project Flume reported in the paper at Wyoming, Replogle, 1983 have functioned satisfactorily for another season. Immediately after the corrections were installed, which involved raising the flume crest by about one-half foot, a large storm filled the upstream canal with sediment to an unmeasured level. Afterwards the flume discharged with a distorted downstream wake that eventually went away. The November canal dryup of 1983 had disclosed a large sandbar a hundred yards upstream and near the north bank. The flume apparently had been swamped with sediment and then had eventually cleared itself over the season. The remaining deposits were out of range of causing flume problems.

Streamflow measurements during this time, spring and summer of 83 had shown a slight shift in calibration compared to the original computer predictions. These seem to be explained by rerunning the computer model assuming an average sediment depth of 2 feet.

Further observation during the dryup of 1984 and 85 have shown that the major sediment now entering the channel is from side inflows due to local rainstorms. These are insignificant.

A structural problem occurred with the large flume on the Salt River Project South Canal. The designers added some extra overfall depth after the experience with inadequate overfall (due to field charge in channel grade that failed to be carried over to the original flume design) on the first large flume described above. The canal lining was poor and the extra energy from the excess overfall eventually loosened some downstream slab parts. These were repaired in the fall of 1984, but in 1985 more extensive repairs were made including new side walls. A revised calibration was computed for the slightly changed dimensions.

Errors Due to Non-Level Flumes

A manuscript with a similar name was prepared in 1985. It is back for revision and changes in presentation.

Sediment-Carrying Flumes

A flume design for sediment transport capability was built but not tested due to diversion of efforts to install the new weigh tank system for the Hydraulics Laboratory. A method for accurately metering sediments into the flow is ready but a recovery tank is desirable to protect the system pumps. The test is to evaluate a throat shaped so that the velocities remain high at low flows. The first test is to be on a sill that is lower than usually encountered, and which would ordinarily go to unstable Froude Number flow except that the sidewalls slope inward and thus provide a changing (decreasing area ratio at higher flows).

Flume Standards

At the request of an ASAE (American Society of Agricultural Engineers) committee, standards based on our recommendations in the book are planned. Only the basic outline and scope have been defined.

Handbooks

A chapter on flumes was prepared for a Civil Engineering Handbook. It contains a shortened version of the original book plus an addition for circular flumes.

A second handbook for the American Society of Civil Engineers, ASCE, is under way. It will include a general survey of all meters for irrigation and drainage applications and concentrate on channel flows. Control systems for canals may be added.

SUMMARY

Three manuscripts and a handbook chapter were prepared relating to flume design. Two papers attempt to simplify design selections and give due regard to channel conditions. The previously developed computer model that served to generate the selection designs in the book was again used to develop a basic selection chart where an area ratio is used to prescribe or determine the approach channel Froude Number. The chart is applicable for rapid selection of rectangular and triangular flumes or broad crested weirs for any channel shape. One paper concentrates on development of the method and the second on its application.

On the large flumes (1500-2000 cfs) in the main canals of the Salt River Project Irrigation District, one has operated very satisfactorily since changes to correct installation mistakes were corrected. A storm that moved heavy sediments into the canal caused a small, barely detectable, temporary shift in calibrations, but the sediments cleared after the storm flows ceased. A structural problem related to downstream canal lining strength on the second flume was corrected in the fall of 1985.

The third manuscript, dealing with non-level flumes, was prepared in 1985. It is back for revision and changes in presentation. A high sediment carrying flume design was constructed but awaits testing. A handbook chapter on flumes was prepared which included a summary of previous work and additions for circular flumes. Other handbook chapters and standards on flumes are under way.

Future problems to consider

1. Use of flumes with control systems.
2. Wide-range flumes.
3. Minimum structure portable furrow flumes.
4. Head detection improvements for interfacing with control systems.
5. Sediment resistance.
6. Flumes used with sediment sampling systems.
7. Eddy-loss determinations for various outlet configurations.

PERSONNEL

Replogle, J.A., Clemmens, A.J.

TITLE: PHOTOSYNTHESIS AND PLANT WATER STATUS OF COTTON UNDER TRICKLE AND LEVEL-BASIN IRRIGATION

NRP: 20740 CRIS WORK UNIT: 5542-20740-003

INTRODUCTION

Conservation of irrigation water is of critical importance for the arid southwest. New technologies for water conservation, such as drip irrigation and new crop cultivars are currently being developed. Trickle irrigation has already been shown to be economically feasible for southwest cotton production (Wilson and Ayer, 1984, and Ayer et al., 1984). Cotton lint yields of as much as 2250 kg/ha have been achieved using trickle irrigation in central Arizona (Taylor et al., 1983). Trickle irrigation has also been reported to be effective when the amount of water applied is as little as 60% of consumptive use (Hofmann et al., 1985). Less is known about the effects of frequently applied trickle irrigation on the physiology of cotton. The objective of this experiment was to monitor selected physiological characteristics of a short staple cotton under daily trickle and weekly and bi-monthly level-basin irrigation regimes.

MATERIALS AND METHODS

This study was conducted using a subset of the treatments in a larger field experiment. For a detailed account of field procedures see French et al. (1985) and Bucks et al. (1986). Planting occurred on 11 April 1985 at the University of Arizona Maricopa Agricultural Center following a pre-plant irrigation. An individual plot consisted of six 10 m beds, with 1.0 m bed spacing. A neutron probe access tube was located in the center of one of the middle beds in each plot. The cultivar used in this experiment was Deltapine 90. The experimental design was a randomized complete block with three replications.

The three irrigation treatments were as follows: (1) a single surface trickle irrigation line per two rows irrigated daily; (2) level-basin irrigated weekly; and (3) level-basin irrigated bi-monthly (every other week). Volumetric soil water content was measured the day of and two days after each irrigation of the level-basin irrigated plots and once every two weeks for the trickle irrigated plots.

A Li-Cor 6000 portable photosynthesis instrument was used to measure net photosynthesis (Pn), transpiration (Tr), stomatal conductance (Cs), leaf temperature (Tl), and ambient temperature (Ta). Measurements were taken on a single fully sunlit leaf near the top of the canopy from three plants in each plot. All three plants were located in the rows in which the neutron probe access tubes were located. The same leaves were immediately removed from the plant at the petiole and placed in sealed thermocouple psychrometer chambers. The chambers were placed in a cooler

and returned to the laboratory. Leaf water potentials (WP) were measured using the dew point method after 12 to 16 hr of equilibration at approximately 23°C.

Measurements were made, whenever possible, the day before and the day after a level-basin irrigation between 1100 and 1200 hr. Measurements were made on a total of 8 days between June 13 (day 164) and July 9 (day 190), the period of peak water use during the growing season.

RESULTS AND DISCUSSION

Soil moisture content tended to decrease over the length of the experiment for all three irrigation treatments (Figure 1). The two level-basin treatments, of course, showed sharp increases in soil moisture following irrigations, but the average rate of decrease in soil moisture was similar for all three treatments and indicated that the irrigations were not sufficient to replace water lost to evapotranspiration during the study. The daily trickle irrigation treatment appears to have lower average soil moisture content than either level-basin irrigation treatment, yet the amount of water applied was calculated so that all three treatments received approximately the same amount of irrigation water over the coarse of the growing season. The daily, weekly, and bi-monthly treatments received 876, 994, and 977 mm of water, respectively, over the course of the growing season. The trickle system, however, delivered water to the bottom of the furrow so that soil water content was probably underestimated by the neutron measurements which were taken from the center of the bed.

WP measurements (Figure 2) indicate that the daily trickle irrigated plants maintained a fairly constant WP with all measurements between about -1.25 and -1.50 MPa. Leaf water potential of both level-basin irrigated plots dropped to significantly lower levels on days preceding an irrigation, days 176 and 190, for example. On these two days the leaves of the bi-monthly irrigated plants were visibly wilted.

Pn (Figure 3) of the daily irrigated plants was also significantly higher than the level-basin irrigated plants on days 176 and 190, indicating that the level-basin irrigated plants experienced a water stress-induced drop in productivity prior to irrigation. WP and Pn were less dependent on climatic conditions than Tr (Figure 4), Cs (Figure 5), or the temperature differential (TD) between air and leaf temperature (Figure 6), all of which showed a strong dependence upon air temperature and vapor pressure deficit (Figure 7). Tr, Cs, and TD measurements also indicate that the level-basin irrigated plants were under greater stress than the daily irrigated plants just prior to irrigation.

It is interesting to note that the daily irrigated plants used more water than either of the level-basin irrigation treatments, as indicated by their consistently higher Tr and Cs rates, yet they were under less stress and were more productive, even though all plots received the same amount of irrigation water.

SUMMARY AND CONCLUSION

The period during which these measurements were taken coincided with the period of peak water use during the growing season. Later during the growing season the soil moisture content increased and the plants were under less stress. These measurements also coincided with the first month of flowering, a critical period of development for cotton. The deficit irrigation during this critical period and the resulting stress experienced by the level-basin irrigated plants caused a reduction in productivity that resulted in significantly lower yields. Cotton lint yields of the daily, weekly, and bi-monthly irrigated plots were 1602, 1179, and 1260 kg per ha, respectively.

When cotton is irrigated with less than the optimum amount of water it appears that a daily trickle irrigation regime results in less stress and greater productivity than less frequently applied level-basin irrigations.

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PERSONNEL

S.G. Allen, D.A. Bucks, and D.A. Dierig

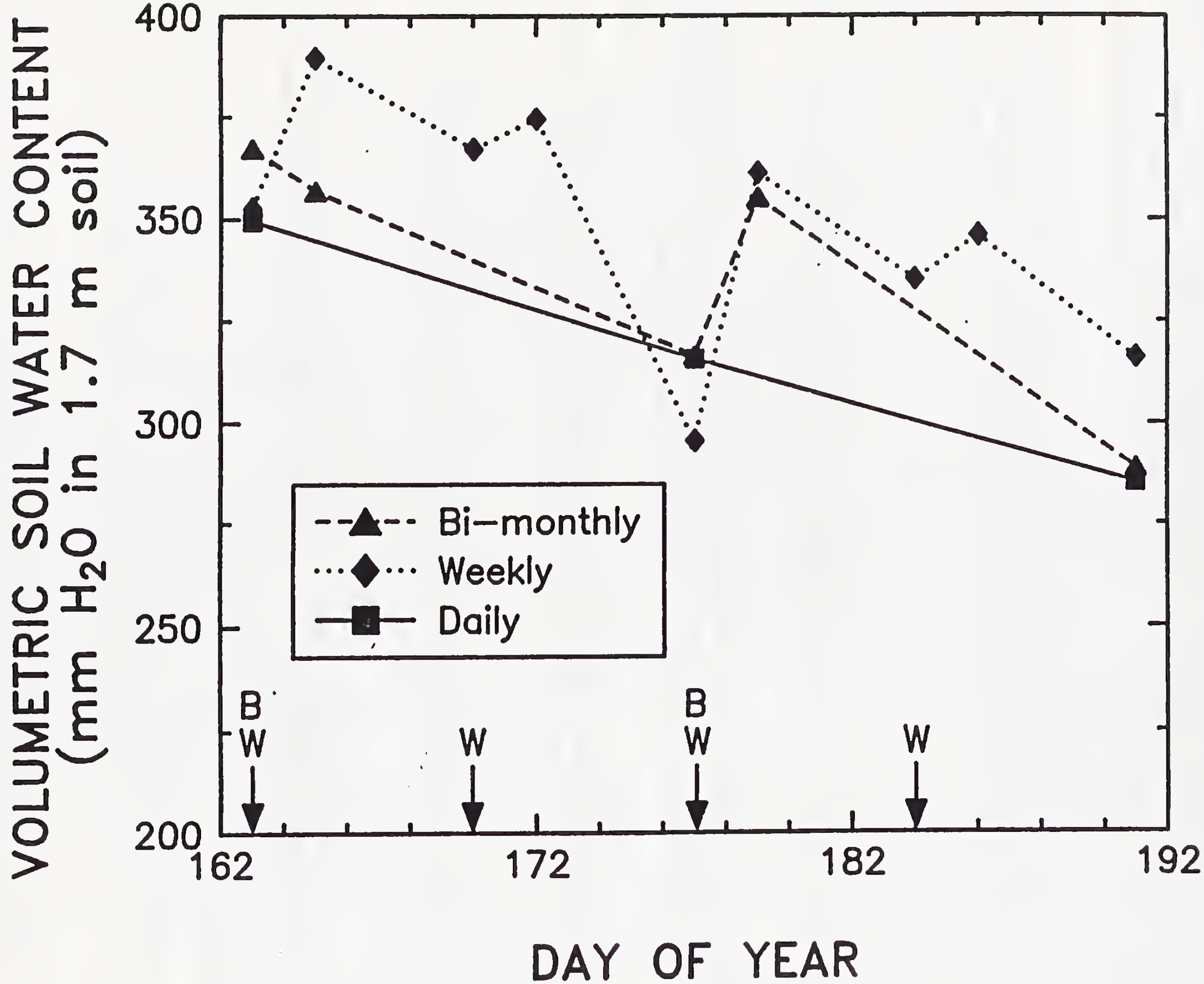


Figure 1. Volumetric soil moisture content of daily trickle, and weekly and bi-monthly irrigated plots. Each point represents mean of three measurements.

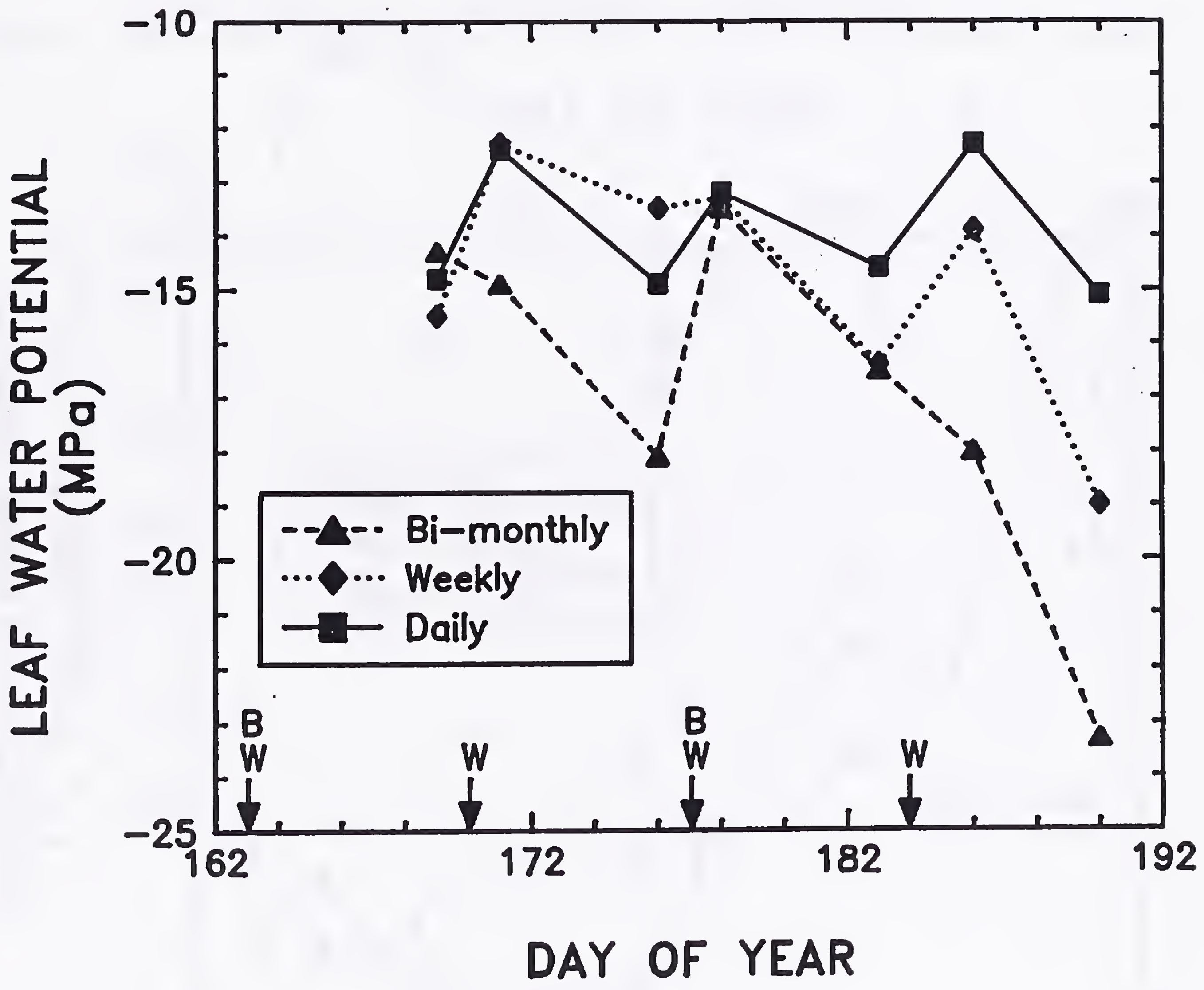


Figure 2. Leaf water potential of daily trickle, and weekly and bi-monthly irrigated cotton. Each point represents mean of 9 measurements.

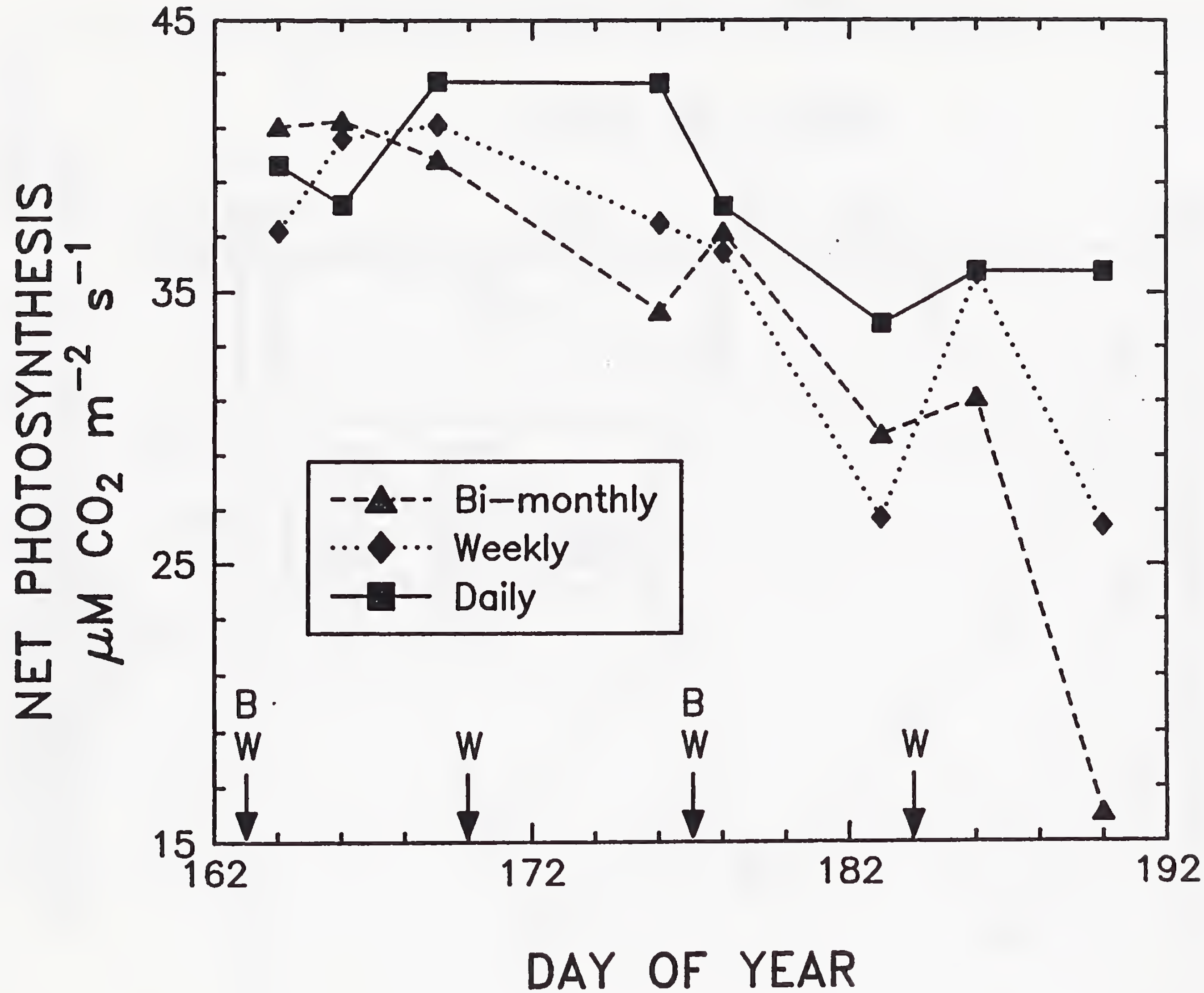


Figure 3. Net photosynthesis of daily trickle, and weekly and bi-monthly irrigated cotton. Each point represents mean of 9 measurements.

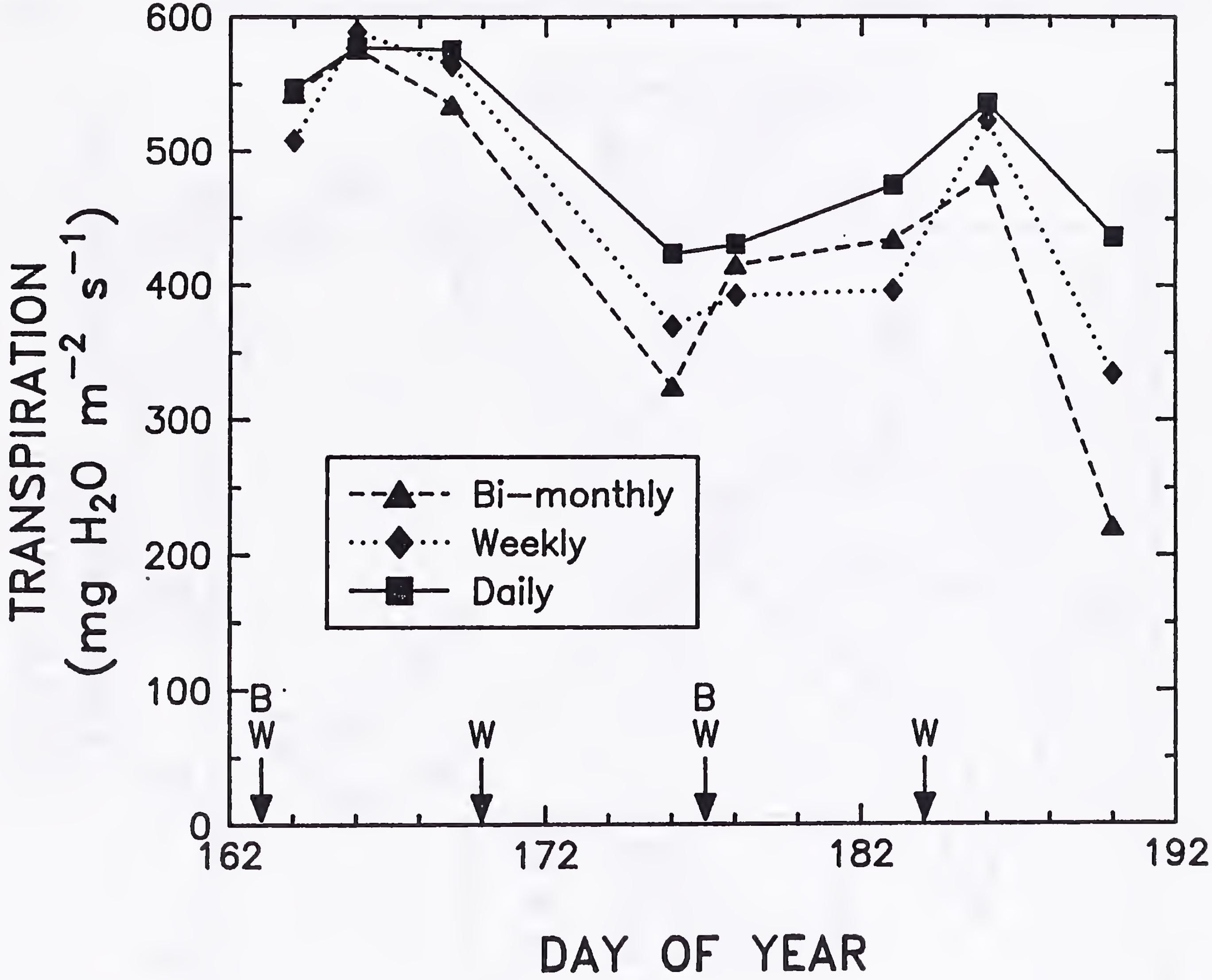


Figure 4. Transpiration of daily trickle, and weekly and bi-monthly irrigated cotton. Each point represents mean of 9 measurements.

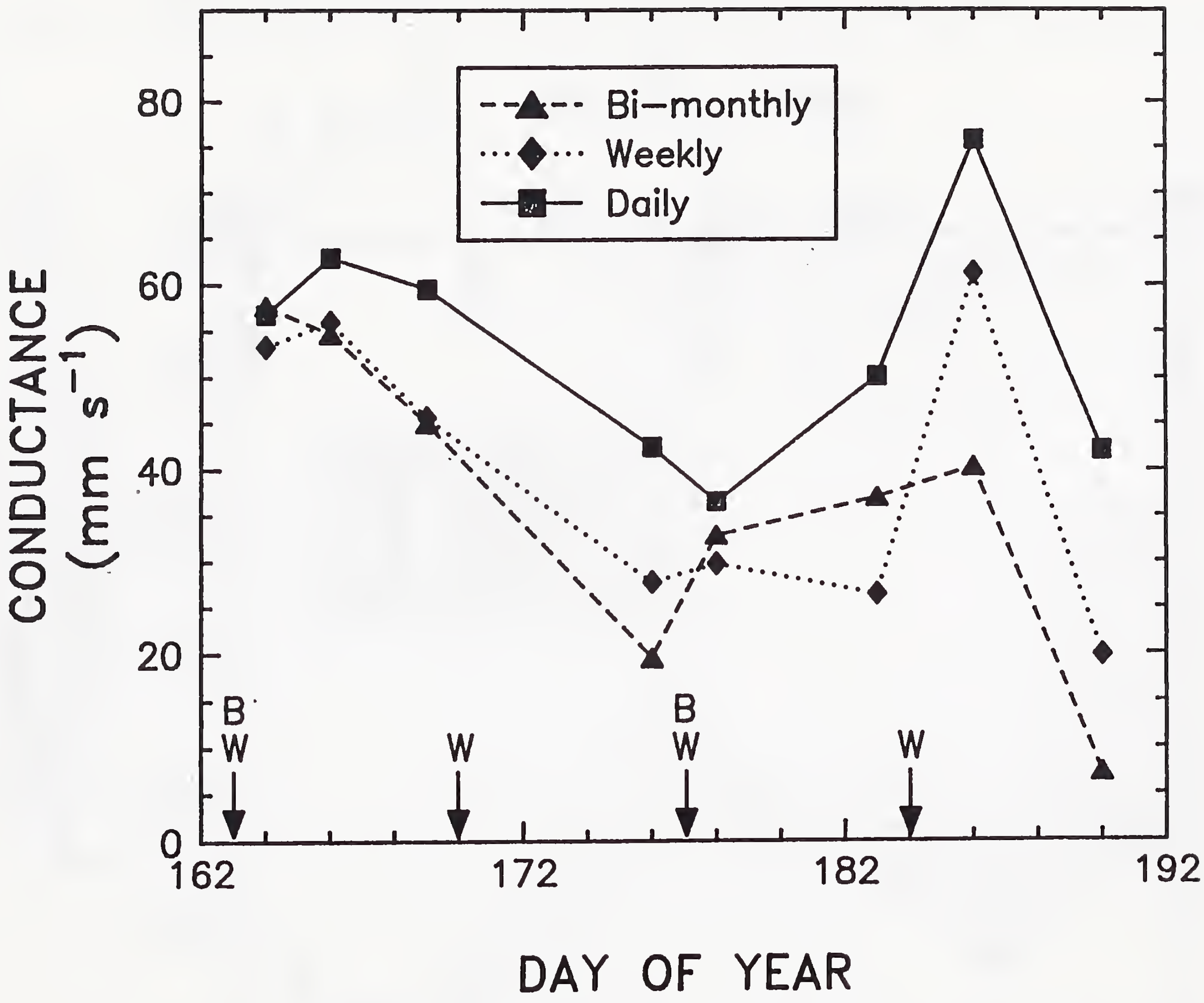


Figure 5. Conductance of daily trickle, and weekly and bi-monthly irrigated cotton. Each point represents mean of 9 measurements.

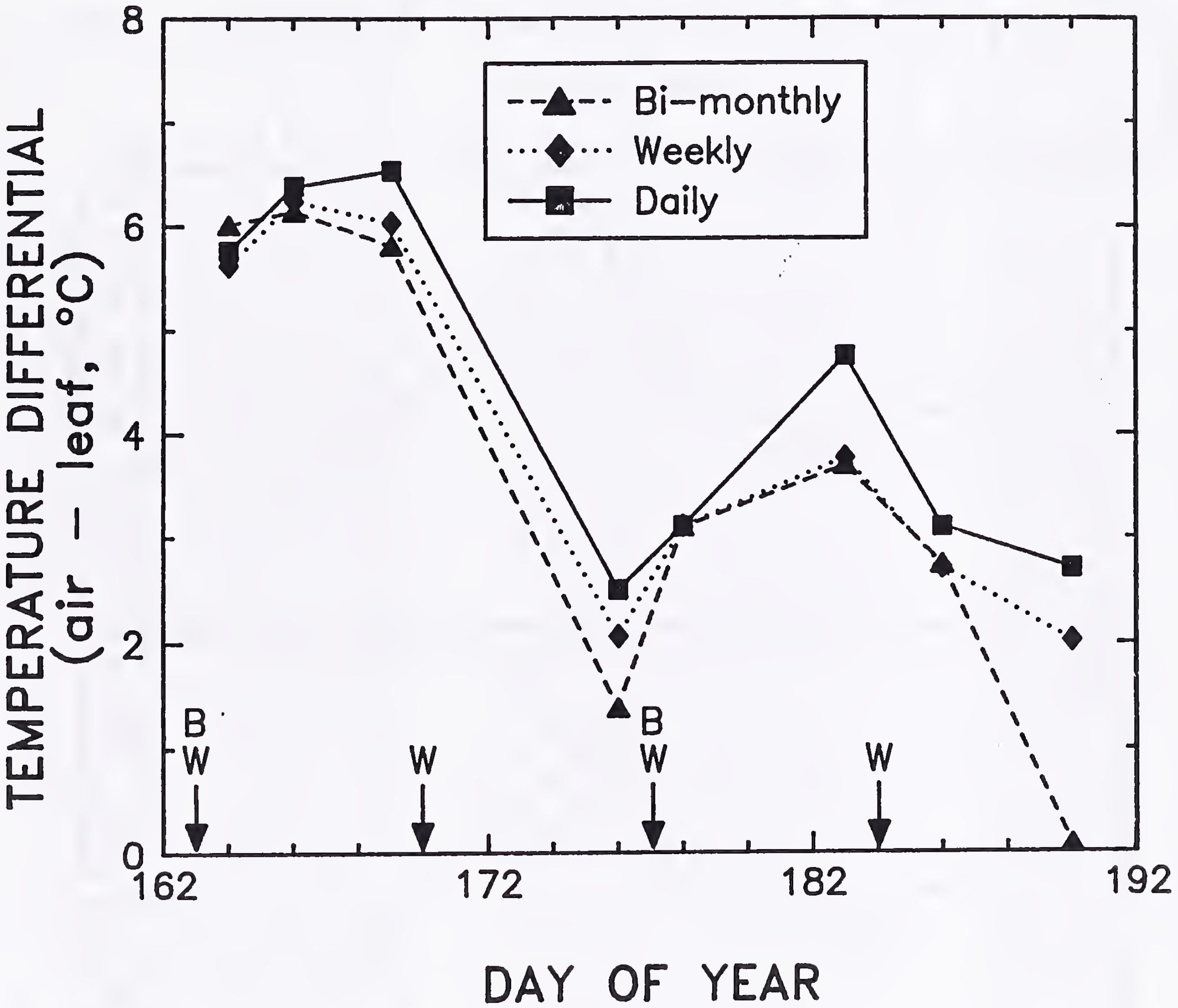


Figure 6. Temperature differential (air-leaf, °C) of daily trickle, and weekly and bi-monthly irrigated cotton. Each point represents mean of 9 measurements.

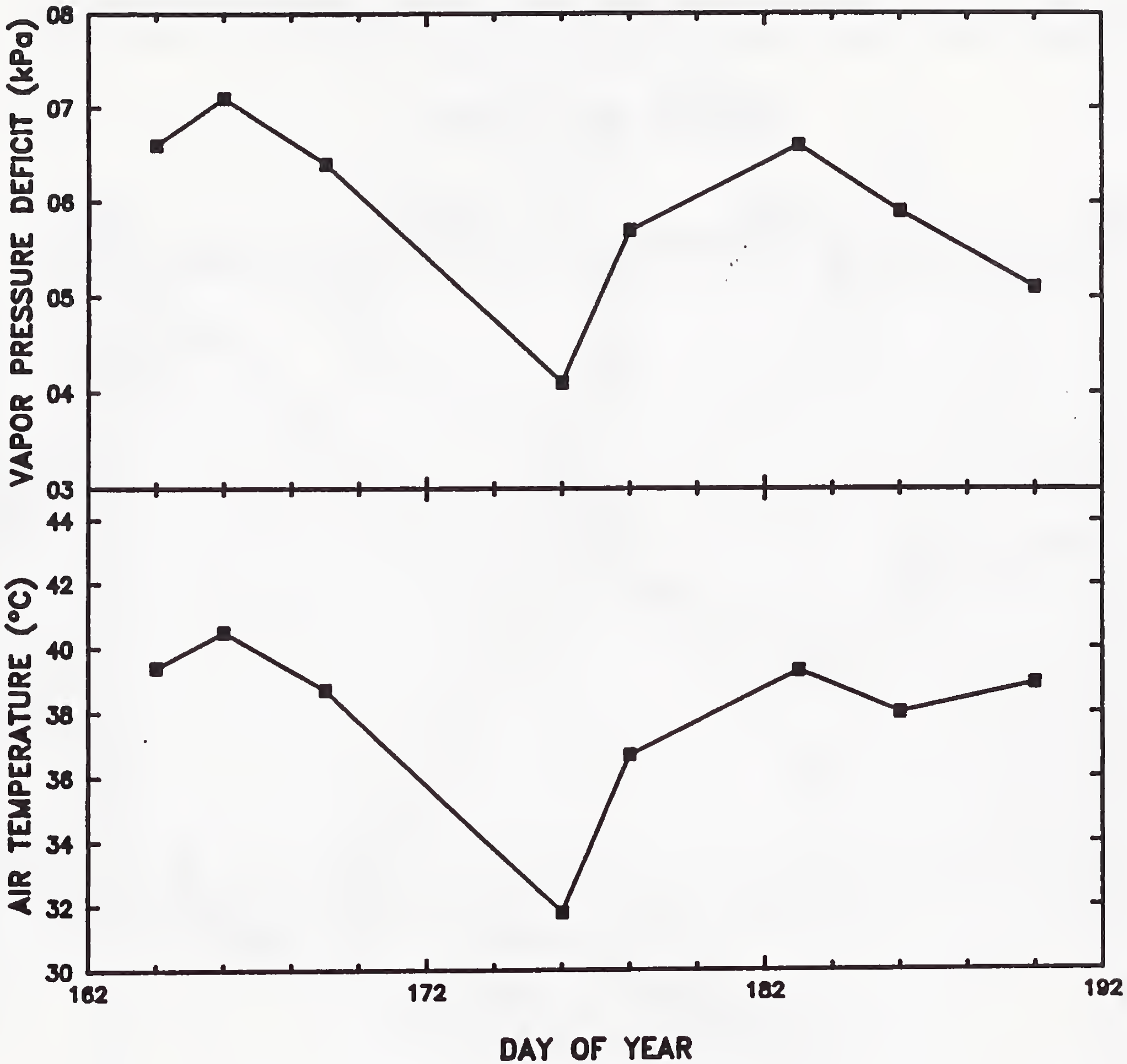


Figure 7. Vapor pressure deficit (top) and air temperature (bottom) at 1200 hr MST for days on which physiological measurements were taken.

TITLE: TRICKLE AND LEVEL BASIN IRRIGATION OF COTTON ON A SANDY LOAM SOIL

NRP: 20160 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION

The trickle and level-basin irrigation management research on cotton began in 1983. The objective of the 1985 experiment was to determine the effects of irrigation water placement and frequency for trickle and level-basin irrigation methods under optimum moisture conditions for conventional and narrow-row plantings using the newer short-stable cotton varieties.

Field Procedures

Cotton varieties of DPL-775, DPL-90, DPL-41, and Stoneville 825 were planted on the conventional 1.0 m (40 inch) row spacing on April 5, 1985 at the Maricopa Agricultural Center, University of Arizona, on a sandy loam soil. At the same time DPL-775, DPL-90, DPL-30, and DPL-70 were planted on the narrow-row, 0.75 m (30 inch) row spacing. A Stanhay precision planter was used with the same planting rate on both row spacings. To give each row spacing equal opportunity for germination both row spacings were irrigated up. An excellent stand was obtained on both row spacings with plant densities of 81,500 and 108,700 plants per hectare on the conventional and narrow row plantings, respectively. Each treatment plot was 10 m (33 feet) long and consisted of 24 rows with 6 rows of each of the four varieties, as shown in Figure 1. The varieties were randomized within the five irrigation treatments which were replicated six times.

The five irrigation treatments for 1985 were as follows: (1) a single trickle irrigation line per two rows irrigated daily; (2) a single trickle line per two rows irrigated twice weekly; (3) a single trickle line per three rows irrigated daily; (4) level-basin every furrow irrigated weekly; and (5) level-basin, every furrow irrigated biweekly (every two weeks). Irrigation scheduling was based on historical (Erie et al., 1982) and meteorological estimates of evapotranspiration with conventional and narrow-row cotton receiving the same water applications. Regular irrigation treatments commenced on May 29 and continued through September 23. Soil water was measured weekly on three replicates to a depth of 1.8 m (6 ft) with neutron moisture meters on treatments 1, 4, and 5 for DPL-775 and DPL-90 varieties. Treatment 1 was monitored to show placement and uniformity of soil water contents, whereas treatments 4 and 5 and were used for estimating the water consumed by the cotton crop.

The trickle line used was the Irridelco[1/] system with in-line 2L/h (0.5 gal/h) emitters placed 1 m (40 in) apart along the line. The water supply was from two farm wells and was filtered through sand filters followed by a screen filter with 74 micron (200 mesh) openings. The electrical conductivities of the two wells were about 1.1dS/M (690 mg/l) and 3.2dS/M (2070 mg/l), respectively. Approximately two thirds of the water applied was from the good quality well. The irrigation water applied was measured through household, 2 cm (0.75 inch) diameter, propeller-type water meters. The furrow plots were irrigated by delivering water through a 15 cm (6 in) main line followed by 5 cm (2 in) lateral lines to the individual plots. Water applied was measured through a 10 cm (4 in) diameter, propeller-type water meter for all furrow irrigations.

Fertilizer applications were made through both irrigation systems in the form of liquid UN_{32}. A total of 297 kg/ha (265 lbs N/AC) was applied at a rate of 34 kg(30 lb) of N per week over a nine-week period beginning on June 3 and finishing on August 4 on all treatments. Cotton leaf petiole samples were taken beginning on June 12, continued every two weeks through September, and analyzed for nitrate-nitrogen. In addition, the soil was sampled in October to a 120 cm (4 ft) depth and analyzed for nitrates and total dissolved salts.

The cotton field was defoliated in early and late October. On November 4, two rows 9.1 m (30 ft) long were harvested from the 6 row plots for all varieties and row spacings on treatments 1, 2, 4, and 5 except three rows were harvested for treatment 3 (a single trickle line per three cotton rows irrigated daily).

RESULTS AND DISCUSSION:

The total amount of water applied plus rainfall on trickle and level-basin is shown in Table 1. More water was applied to the level-basin plots early in the season to get adequate coverage over the plots, which accounted for the higher totals on the level-basin plots. Some of this extra water applied may have been lost to deep percolation. The number of irrigations ranged from 102 on the daily trickle (treatments 1 and 3) to 9 on the biweekly level-basin practice (treatment 5). The 1985 consumptive water use for cotton was 1002 mm (39.5 in) on the level-basin irrigation treatments (Figure 2).

Leaf petiole samples taken throughout the growing season (Table 2) indicate that an adequate nitrogen supply was available to the cotton plants and that a similar nitrogen use pattern with time resulted for the two row spacings, different varieties, and various irrigation treatments. Nitrate-nitrogen levels were sufficient at the beginning of sampling and decreased gradually through the growing season until levels were very minimal at seasons end. Soil salinity was low considering water quality and residual soil nitrogen was also low at the end of the growing season (Table 3).

[1/] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

A maximum lint yield of 2135 kg/ha(1906 lb/ac, 3.8 bales/ac) was achieved by the DPL-90 variety with the single trickle irrigation line per every two rows irrigated daily (treatment 1) on the narrow-row spacing, as shown in Table 4. Lint yields from the single trickle line per two cotton rows (treatment 1) irrigated daily produced 20% and 10% more lint than the level-basin irrigation method (treatment 4) irrigated weekly on the conventional and narrow-row spacings, respectively. Cotton lint yields were reduced by 13% and 24% on the single trickle line per three cotton rows (treatment 3) as compared with a single trickle line per two cotton rows (treatment 1) irrigated daily on the conventional and narrow-row spacings, respectively. The daily versus twice weekly trickle irrigations (treatment 1 and 2) indicated a 6% and 13% increase for the conventional and narrow-row plantings, respectively, in favor of the more frequent trickle irrigation for the conditions of this experiment.

The weekly level-basin irrigation treatment outyielded the biweekly schedule by 10% on the conventional spacing but by 33% on the narrow-row spacing. This may have resulted from more irrigation water applied to the weekly treatment early in the growing season in order to get adequate coverage over the plots. Also, temperatures were unseasonably hot in late June and early July, which may have had a beneficial effect on the weekly treatments and the narrow-row spacing. Varietal response indicates that the new DPL-775 variety was best for both row spacings for this particular year. Overall the narrow-row spacing outyielded the conventional row spacing by 15%, which could be attributed in part to the 33% higher plant population on the narrow-row compared with conventional plantings.

SUMMARY AND CONCLUSIONS

Both trickle and level-basin irrigation methods, when properly managed and operated, achieved high cotton yields and water use efficiencies on a low water holding capacity soil in 1985. A maximum lint yield of 2135 kg/ha (3.8 bales/ac) was achieved for the DPL-90 variety with a single trickle irrigation line per every two rows irrigated daily on the narrow-row spacing although the new DPL-775 was best overall. The single trickle line per every two rows irrigated daily averaged 10% more lint cotton than the level-basin, every furrow irrigated weekly for both row spacings. The narrow-row plantings (0.75 m between rows) outyielded the conventional planting (1.0 m between rows) by 15%, partly because of higher plant populations. Daily trickle irrigations averaged about 10% more yield than the twice weekly trickle irrigations, and the weekly level-basin irrigations averaged over 20% increase in yield over the biweekly (every two weeks) level-basin irrigations. Light-frequent irrigations can be advantageous for nonhomgenous soils in the semiarid southwestern United States and the newer short-stable cotton varieties appear to have a lower water requirement than those planted in the 1970's.

PERSONNEL:

D. A. Bucks and O. F. French (U. S. Water Conservation Laboratory); D. E. Powers and W. L. Alexander (University of Arizona, Maricopa Agricultural Center).

Table 1. Water applied as irrigation water plus rainfall with trickle and level-basin irrigation systems, 1985.1/

Irrigation Treatment2/	No. of Irrigations	Total Water Applied (mm) 1.0 m Furrows	Total Water Applied (mm) 0.75 m Furrows
1	102	876	883
2	34	870	866
3	102	837	868
4	18	994	1101
5	11	977	1043

1/ Rainfall totaled 30 mm (1.2 in) throughout the growing season.
2/ Irrigation treatments are listed in procedures.

Table 2. Average cotton petiole analyses for Nitrate-Nitrogen (mg/l) with time in 1985.1/

		Sampling Dates						
Spacing	Variety	6/12	6/26	7/9	7/27	8/16	9/1	9/16
	DPL-775	11600	7000	5700	5300	4600	3850	1400
0.75 m	DPL-90	10600	6800	5600	5200	4100	2800	1000
	DPL-30	11500	8000	6500	5700	4400	2900	1350
	DPL-70	10700	7100	6100	5500	4100	2800	1200
	DPL-775	13900	10200	8100	6700	6000	4850	2400
1.0 m	DPL-90	13000	9600	7400	6100	4900	3100	1500
	DPL-41	16700	12200	8400	7300	5600	4000	2600
	Stone. 825	12900	8900	7000	6000	4850	3550	2200

1/ Each number represents mean of 5 irrigation treatments and 3 replications.

Table 3. Soil analysis for the 1985 Cotton Experiment.

	Soil Depths (cm)				
	0-5	0-30	30-60	60-0	90-120
Total Dissolved Salts (g/m^3)	1021	1052	1083	753	676
Nitrate (mg/l) Nitrogen	16	13	14	10	11

Table 4. Average lint cotton yields for trickle and level-basin irrigation methods from machine picked plots on November 4, 1985.

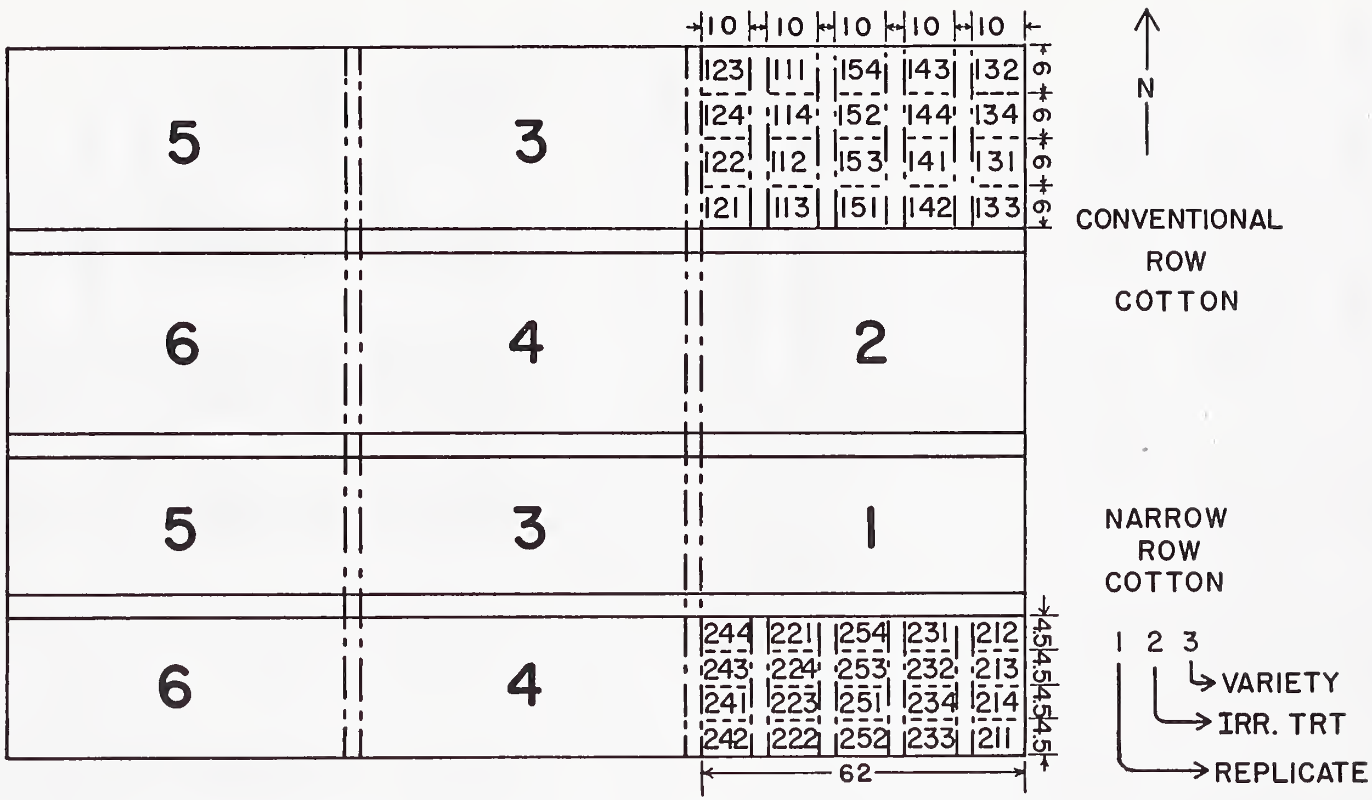
Row Spacing	Cotton Variety	Irrigation Treatment 1/ 1	2	3	4	5	Mean
		Lint Yield (kg/ha)2/					
	DPL-775	1790	1678	1696	1341	1319	1565a3/
1.0 m	DPL-90	1668	1727	1385	1399	1225	1481ab
	DPL-41	1732	1574	1448	1546	1090	1478ab
	Stone. 825	1513	1318	1418	1264	1406	1384b
	Mean	1676a	1574ab	1487bc	1388cd	1260d3/	1477
	DPL-775	1833	1748	1662	2101	1370	1743a3/
0.75 m	DPL-90	2135	1704	1541	1539	1439	1671a
	DPL-30	1904	1829	1560	1807	1267	1673a
	DPL-70	2027	1725	1585	1785	1360	1696a
	Mean	1975a	1752b	1587c	1808b	1359d3/	1696

1/ Irrigation treatments are listed in procedures; each number represents a mean of 6 replications.

2/ 560 kg/ha = 1.0 bale/ac; lint percentage averaged 37.7%.

3/ Means within column and rows with the same letter are not significantly different at the .05 level.

1985 COTTON EXPERIMENT-MARICOPA AGRICULTURAL CENTER



* All measurements in meters

Irrigation Treatments

1. A single trickle line per two cotton rows irrigated daily.
2. A single trickle line per two cotton rows irrigated twice weekly.
3. A single trickle line per three cotton rows irrigated daily.
4. Every furrow with the level-basin method irrigated weekly.
5. Every furrow with the level-basin method irrigated bi-weekly.

Varieties

1. DPL-775	1. DPL-775
2. DPL-90	2. DPL-90
3. DPL-41	3. DPL-30
4. STONE.825	4. DPL-70
1.0 m rows	0.75 m rows

Figure 1. Planting diagram for 1985 cotton experiment at the Maricopa Agricultural Center, Maricopa, AZ.

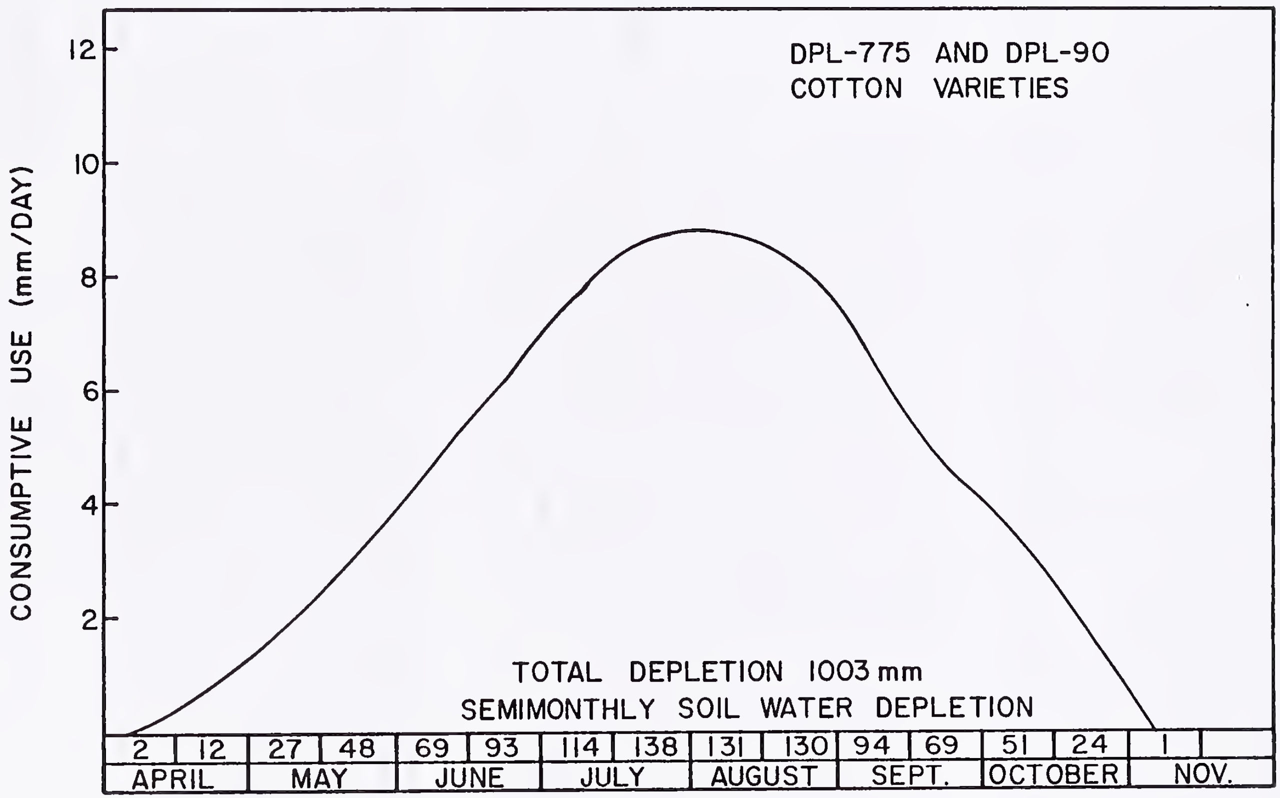


Figure 2. Mean Soil Water Depletion Curve for Cotton Irrigated by the Level-Basin Method at the Maricopa Agricultural Center, Maricopa AZ, 1985.

TITLE: CROP YIELD VARIABILITY IN IRRIGATED LEVEL BASINS

NRP: 20740 CRIS WORK UNIT: 5422-20740-004

INTRODUCTION

Spatial variability in irrigated agriculture has been recognized for many years. However, as limited water supplies, expensive energy, and increasing capital costs force producers to manage resources more efficiently, the effects and limitations imposed by variations in soil parameters and irrigation system behavior become more significant. One serious limitation to optimum design and management of irrigation systems is the scarcity of information on the effects which soil variability and water application uniformity have on crop yield, particularly under reduced water use. An understanding of the expected variability in irrigated crops should not only be used to improve irrigation designs, but alter irrigation water management scheduling practices.

Variability in crop production can be attributed to any number of factors, such as climate, soil, fertility, cultural practices, and irrigation. However, within an irrigated field, climatic and cultural factors are more or less uniform and the spatial distribution of crop yield will be largely influenced by variations in soil and irrigation (Warrick and Gardner, 1983). If the water applied through an irrigation system is distributed unevenly within the field, crop yield may be reduced in some areas due to the effects of insufficient water. Excessive watering may also occur in some portions of the field. Although this can have a negligible effect on yield, excessive moisture is often associated with other factors contributing to yield losses such as, plant lodging, reduced aeration in the root zone, nutrient leaching, and disease. In either case, the distribution of soil water in an irrigated area is closely linked with the efficient use of water, fertilizer, and other production inputs.

Recent research (Seginer, 1978; Stern and Bresler, 1983; Warrick and Gardner, 1983: Feinerman, et al., 1983; Russo, 1984) indicates an increased interest in spatial variability as it affects crop production. It is generally accepted that variability in soil properties and irrigation uniformity is responsible for some of the variability in crop yield. However, information on how much these factors affect yield is quite limited, particularly under surface field irrigation. The objective of this study was to determine the relationship between the uniformity of water applied by the level-basin irrigation method, soil moisture variability and its effect on yield under different levels of irrigation and basin lengths.

FIELD PROCEDURES

The 1985 study was conducted on a variable sandy loam to sandy clay loam field, 168 by 151 m (551 by 825 ft), located on the Maricopa Agricultural Center, University of Arizona, near Maricopa, AZ. Durum wheat

(<u>Triticum</u> <u>durum</u> cv. Aldura) was planted at a rate of 129 kg/ha (115 lb/ac) on the flat in 12 level borders, 14 m wide by 244 m long (46 by 800 ft), on January 3, 1985. The 12 borders were separated into six differential treatments replicated twice, in a randomized block design (Figure 1). Treatments consisted of three irrigation levels and two border lengths. The three seasonal irrigation treatments were designated Wet (I_1), Medium (I_2), and Dry (I_3) and designed to replace 100, 75 and 50 percent of the expected evapotranspiration (ET), respectively. Irrigation scheduling was based on historical (Erie <u>et</u> <u>al</u>., 1981) estimates of evapotranspiration and measured soil moisture depletion, as well as adjusted for the planting date and climatic conditions. Border lengths, designated long and short were 244 and 183 m (800 and 600 ft), respectively.

Before planting, the entire field was plowed, laser-leveled and top-dressed with nitrogen at a rate of 90 kg/ha (80 lb/ac). Neutron access tubes were installed to a depth of 2.1 m (7 ft) and placed at 15 m (50 ft) spacings down the center of each border for a total of 15 access tubes in long orders, and 11 access tubes in short borders (52 tubes in each irrigation treatment). In one of the borders, three additional access tubes were installed at each 15 m spacing for a total of 44 access tubes in that border. (The additional tubes were used in a companion study on infiltration). Figure 1 shows the location of each access tube in the study site. Soil samples were collected in 25 cm (9.8 in) increments to a depth of 100 cm (3.3 ft) before planting and again following harvest at each neutron access tube location. In addition, soil samples were taken periodically throughout the irrigation season at the third, seventh and tenth access tube of each border. These samples are currently being analyzed for soil texture, bulk density, and chemical properties.

The irrigation system was laser-controlled level basins. Rectangular canal gates, 0.61 by 0.71 m (24 by 28 in), were installed in the water supply ditch at the head of each border. The water delivery rate was measured during each irrigation by a flume located in the supply ditch which was connected to an automatic water level recorder (Bos, Replogle, and Clemmens, 1984). The water supply came from two farm wells having electric conductivities of about 1.1 dS/m (690 mg/L) and a combined delivery rate which ranged between 153 and 164 L/s (5.4 and 5.8 cfs). All borders were given a pre-plant irrigation of approximately 127 mm (5.0 in) for plant establishment on December 22 and 23, 1984. In addition, 38 mm (1.5 in) of rainfall occurred on December 27 and 28, 1984. Soil water contents were measured at a 20 and 30 cm depth, and at each subsequent 20 cm interval to a depth of 190 cm at all access tube locations. The neutron moisture meters were calibrated for a typical soil in the field. Soil water content measurements began after plant emergence on February 13. Regular irrigation treatments began March 15 and continued through May 7. The average irrigation amounts and irrigation dates for the four borders in the Wet (I_1) treatment (five irrigations) were 129.6 mm (5.1 in) on March 15, 113.9 mm (4.48 in) on April 3, 103.0 mm (4.05 in) on April 12, 125.8 mm (4.95 in) on April 26, and 102.6 mm

(4.04 in) on May 7. The Medium (I_2) treatment (four irrigations) received average amounts of 140.3 mm (5.52 in) on March 21, 113.8 mm (4.48 in) on April 9, 101.1 mm (3.98 in) on April 18, and 104.4 mm (4.11 in) on May 7. The Dry (I_3) treatment (two irrigations) received average amounts of 133.2 mm (5.24 in) on April 3, and 117.7 mm (4.63 in) on April 18. Fertilizer applications were made through the irrigation water in the form of liquid UN_{32} to all treatments at the early heading stage of crop development. A total of 90 kg/ha (80 lb/ac) was applied on April 3 to the Wet (I_1) and Dry (I_3) treatments, and on April 9 to the Medium (I_2) treatment. Soil water measurements were made at all 52 access tube sites within a treatment, one day prior to irrigation and three days after irrigation. Figures 2-4 show the average soil moisture contents to a depth of 1.6 m (5.3 ft) for the 52 locations within an irrigation treatment and the dates and amounts of irrigation water added for the three treatments. Figures 2-4 also show the estimated field capacity, permanent wilting point, and average soil moisture depletion one day prior to irrigation.

The amount of water applied during each irrigation at a particular access tube site was estimated with the assumption that drainage (if any) and evapotranspiration occurred uniformly throughout the border during the time period between irrigation and the soil moisture measurements taken three days later. The average change between pre-and post-irrigation soil water contents to a depth of 2.0 m (6.6 ft) from all tube sites within a border was subtracted from the average irrigation depth measured at the flume. This difference was then added to the change in soil water contents at the individual sites to obtain the estimated water application depths. The cumulative soil moisture depletion (estimated evapotranspiration) at an access tube site included the sum total of the measured change in soil water contents at an assumed crop rooting depth of 1.0 m (3.3 ft) during drying cycles of the growing season. Added to this was the estimated soil moisture depletion that occurred over the five day interval when an irrigation took place between soil moisture measurements. The total water expense (gross water applied) at each access tube site included all water received by irrigation and rainfall (8.0 mm during the growing season) plus the amount of water consumed prior to irrigation from stored soil moisture.

Meteorological factors were monitored by two portable weather stations equipped with CR21 microloggers. One station was placed near the center of a Wet (I_1) treatment border and the other on a nearby alfalfa field. Advance, recession, and infiltration rates were monitored for all irrigations on one border of the Medium (I_2) treatment. Plant canopy temperature measurements were made periodically using an infrared thermometer (IRT) at each access tube site of four borders (two Dry, one Medium, and one Wet). Plant nitrogen uptake and nutrient levels were obtained periodically at the third, seventh and tenth access tube site location of each border.

Individual grain yield samples were machine and hand harvested between June 10 and June 20. Three transects, 1.27 m (50 in) in width, were established down the length of each border. The row of access tubes with-

in each border served as the center line of the middle transect. The two outer transects were centered a distance of 2.3 m (7.5 ft) from the row of access tubes. Samples ranging between 5.8 and 7.0 m (19 and 23 ft) in length were harvested by a combine along the length of each transect separated by a 0.9 m (3.0 ft) buffer between adjacent samples. The sampling scheme was such that each access tube site was located in the approximate center of a harvested area with an average harvest area of 8.0 m^2 (88.0 ft^2). The borders were harvested in this manner except at the third, seventh and tenth access tube sites. These sites were hand harvested in five or six individual 1.0 m^2 (10.8 ft^2) areas along the middle transect. All harvested plots were measured and the grain was cleaned and weighed for yield determination. From each yield sample centered about an access tube site, grain bushel weight, and protein, nitrogen, and yellowberry percentages were determined.

RESULTS AND DISCUSSION

Grain yield (Y) and the following soil-water variables were estimated by field measurements made at each neutron access tube location (subplots). The soil-water variables include the total seasonal irrigation water applied (Q); total seasonal gross water applied (GWA); cumulative seasonal soil moisture depletion (SMD); and average volumetric soil moisture contents in 1.0 m (3.3 ft) of soil, during the growing season ($\overline{\theta}$), one day prior to irrigation (θ_p), and three days after irrigation (θ_a).

A two factor, randomized block, analysis of variance (Table 1) was performed separately on each variable by treating the variable averages, calculated from subplots within a border, as the independent, random observations. The analysis indicated significant differences ($p < 0.05$) due to irrigation between all variables except θ_a. However, the analysis failed to detect significant effects of border length, or border length-irrigation level interaction for any variable. Table 1 presents the means of each variable by irrigation treatment and by border length. The results of the Student-Neuman-Keuls multiple comparison procedure for testing treatment means are also indicated in Table 1. Means followed by a different letter are significantly different at the 95 percent level of confidence. The results indicate that the irrigation treatments produced significantly different evapotranspiration (SMD) and yield between all three levels of irrigation. Seasonal average soil moisture contents ($\overline{\theta}$) and the average soil moisture contents one day prior to irrigation (θ_p) were significantly lower in only the Dry (I_3) irrigation treatment compared with the Wet (I_1) and Medium (I_2) treatments.

Tables 2 - 5 present the means, as well as, the ranges, standard deviations, and coefficient of variations for grain yield (Y) and the soil-water parameters. The data of Table 2 were derived from all subplots within all three treatments (n=156). The data of Tables 3, 4, and 5 were derived from the subplots within the Wet (I_1), Medium (I_2), and Dry (I_3) treatments, respectively; where part (a) includes all 52 subplots (both long and short borders), part (b) includes the two long borders only (30 subplots), and part (c) includes the two short borders only (22 subplots) within an irrigation treatment.

An indicator of variability that is commonly used in irrigation uniformity studies is the coefficient of variation (CV). When considering all 156 subplots, the data of Table 2 indicate that the greatest variability occurred in yield (47.6 percent) followed by the variability in seasonal irrigation water applied, Q (31.9 percent). The variability in the estimated evapotranspiration (25.6 percent) was considerably more than that of the average seasonal soil moisture content (15.3 percent). Thus over this wide range in water application, much of the variability in yield appears to be primarily associated with differences in Q.

Figure 5 shows the combined grain yield-water application data and the linear regression function derived from all 156 subplot observations in 1985. The regression indicates that about 82 percent of the variability in yield can be explained by the variability in Q, while the rest stems from the combined effects of variations in all other factors (soil, plant, sampling error, etc.) Figure 6, which shows the linear relationship between grain yield and evapotranspiration, indicates that yield is also significantly correlated with ET (R^2 = 0.81), which in turn is dependent upon Q.

The data of Tables 3, 4, and 5, however, suggest that soil, crop, or other factors were responsible for a considerably large amount of the variance in yield within treatments. Part (a) of these tables (all subplots within all borders of a treatment) show that the coefficient of variation in seasonal water applied, Q, was only 6.3, 6.8, and 11.7 percent for the Wet (I_1), Medium (I_2) and Dry (I_3) treatments, respectively. However, the coefficient of variation for grain yield was nearly twice (12.2 percent) that of Q in the Wet (I_1) treatment and about three times (20.1 and 34.3 percent) greater than that of Q in the Medium (I_2) and Dry (I_3) treatments, respectively. The data also indicate that the variability in yield increased somewhat proportionately with the level of water deficit suggesting that the combined interaction between irrigation amount and the variability in other factors which limit yield have a greater impact on yield uniformity at reduced levels of water use. This trend was similar in the relationship between irrigation level and the variability in evapotranspiration (SMD) which was 8.0, 11.8, and 13.2 percent for the Wet (I_1), Medium (I_2), and Dry (I_3) treatments, respectively. The coefficient of variations for $\overline{\theta}$ indicate only slight differences in the variability of the seasonal average soil moisture contents between treatments. However, the variability in soil moisture contents, which is influenced by variations in soil, crop, and other factors, as well as by nonuniformity in water application, was considerably greater than that of Q within the three irrigation treatments. Variation in the average soil moisture contents due to other factors besides irrigation uniformity was approximately 5.8 percent ($CV_\theta - CV_Q$) for all treatments, which could be interpreted in a practical sense as the amount of variation in soil moisture storage capacity throughout the field.

Relationships between grain yield (Y), seasonal water applied (Q), gross water applied (GWA), and soil water contents (θ_p, $\overline{\theta}$, θ_a) were obtained by calculating the correlation coefficients (r) between each pair of variables. The results, summarized in Table 6, show the correlation

coefficients for the 52 subplots within each treatment. The correlation coefficients between yield and the three soil moisture content averages ranged between 0.36 and 0.52 with the lowest correlation (0.36) obtained between Y and θ_p in the Medium (I_2) treatment. Generally, the data of Table 6 indicate that differences in soil moisture contents were responsible for about 22 percent of the variability (average R^2 value) in yield, regardless of irrigation treatment. On the other hand, however, the relationship between the soil moisture contents and water application were uniquely different between the three irrigation treatments. For the Wet (I_1) treatment, there was a significant, but negative correlation between Q and all three soil moisture content averages (θ_p, θ_a, and $\overline{\theta}$). Within the Medium (I_2) treatment, there was essentially no correlation between Q and soil moisture contents averages (θ_p, θ_a, and $\overline{\theta}$). For the Dry (I_3) treatment, there was a significant, positive correlation between Q and θ_a (soil moisture contents after irrigation) but only a slightly positive correlation between $\overline{Q}$ and either θ_p or θ. It can also be seen in Table 6 that the correlation coefficients between Y and Q in the Wet (I_1) and Dry (I_3) treatments are generally reflected in the relationship found between the soil moisture contents and Q in those treatments. However with the Medium (I_2) treatment, Y and Q are significantly correlated, but θ and Q are uncorrelated. In all three treatments, however, the seasonal evapotranspiration (SMD) was related positively to Q, and in turn yield was related positively to SMD.

SUMMARY

Spring wheat, planted in January 1985 and irrigated by laser-leveled basin systems, was studied in central Arizona to determine the effect on grain yield and its variability as influenced by the amount of applied irrigation water, the size of the irrigated border, and the uniformity of water application. An understanding of the expected variability in irrigated crops should improve irrigation designs and water management scheduling practices.

The 1985 field study involved three levels of irrigation amount and two lengths of irrigated border. Grain yield, harvested in June 1985, was found to increase significantly with the amount of water application. However, the variability in grain yield increased as the level of water use was reduced. No significant difference in grain yield was detected between borders of differing length. The uniformity of water application and the variability in soil moisture contents were similar under the three irrigation levels. It was determined that the variability in soil moisture contents was responsible for approximately 22 percent of the variability in grain yield indicating that other soil and crop-related factors had a significant influence on yield. Further analysis is in progress to evaluate the variability of soil physical and chemical properties, infiltration rates, plant nutrient uptake, and plant canopy temperatures. A general recommendation for the irrigation farmer with a nonhomogenous soil and an efficient irrigation system is to schedule irrigations for maximum yields with a corresponding seasonal evapotranspiration rate in order to minimize spatial variabilities.

Plans are to conduct a second study at the same field site in 1986. That study will include spring wheat planted in December 1985, followed by cotton planted in July 1986. In addition to irrigation amount and uniformity, the 1986 field study will also investigate the effects of irrigation water quality on yield. However, there will be no differences in border size during the second study.

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PERSONNEL

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Table 1. Irrigation and border length treatment means* for grain yield (Y), seasonal irrigation water applied (Q), seasonal gross water applied (GWA), seasonal soil moisture depletion (SMD), and the average volumetric soil moisture contents, 1 day prior to irrigation (θ_p), 3 days after irrigation (θ_a), and during the growing season ($\overline{\theta}$).

Variable		Irrigation Treatment Wet	Medium	Dry	Border Length Mean
Grain Yield, Y (kg/ha)	Long	5292	3772	1527	3530[a]
	Short	5057	4161	1391	3536[a]
	Mean	5175[a]	3967[b]	1459[c]	
Total Seasonal Irrigation Water Applied, Q (mm)	Long	567.2	455.4	269.4	430.7[a]
	Short	582.5	463.8	232.4	426.2[a]
	Mean	574.9[a]	459.6[b]	250.9[c]	
Total Seasonal Gross Water Applied, GWA (mm)	Long	638.0	545.8	380.1	514.6[a]
	Short	653.4	546.2	334.2	511.3[a]
	Mean	645.7[a]	546.0[b]	357.2[c]	
Measured Seasonal Soil Moisture Depletion, SMD (mm)	Long	567.3	447.4	326.8	447.2[a]
	Short	562.7	455.3	295.2	437.7[a]
	Mean	565.0[a]	451.4[b]	311.0[c]	
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation, θ_p (m/m)	Long	0.179	0.160	0.143	0.161[a]
	Short	0.176	0.161	0.137	0.158[a]
	Mean	0.178[a]	0.161[a]	0.140[b]	
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation, θ_a (m/m)	Long	0.254	0.237	0.240	0.244[a]
	Short	0.252	0.240	0.226	0.239[a]
	Mean	0.253[a]	0.239[a]	0.233[a]	
Seasonal Average Volumetric Soil Moisture Contents, $\overline{\theta}$ (m/m)	Long	0.218	0.205	0.187	0.203[a]
	Short	0.216	0.208	0.183	0.202[a]
	Mean	0.217[a]	0.207[a]	0.185[b]	

* Means followed by different letters are significantly different at the 95 percent level of confidence.

Table 2. Means, ranges, standard deviations (SD), and coefficient of variations (CV) of grain yield, total seasonal irrigation water applied, total seasonal gross water applied, seasonal soil moisture depletion, average soil moisture contents 1 day prior to irrigation, average soil moisture contents 3 days after irrigation, and seasonal average soil moisture for all treatments combined (N=156).

Variable	Symbol	Units	Range	Mean	SD	CV (%)
Grain Yield	Y	kg/ha	638.8 to 6508.8	3533.0	1682.0	47.6
Total Seasonal Irrigation Water Applied	Q	mm	188.5 to 700.7	428.8	136.6	31.9
Total Seasonal Gross Water Applied	GWA	mm	273.3 to 772.1	517.1	124.7	24.1
Measured Seasonal Soil Moisture Depletion	SMD	mm	208.6 to 667.0	443.2	113.3	25.6
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation	θ_p	m/m	0.091 to 0.219	0.159	0.031	19.5
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.140 to 0.289	0.242	0.029	12.0
Seasonal Volumetric Average Soil Moisture Contents	θ	m/m	0.115 to 0.254	0.203	0.031	15.3

Table 3. Means, ranges, standard deviations (SD), and coefficient of variations (CV) of grain yield, total seasonal irrigation water applied, total seasonal gross water applied seasonal soil moisture depletion, average soil moisture contents 1 day prior to irrigation, average soil moisture contents 3 days after irrigation, and seasonal average soil moisture for (a) subplots within all four borders (n=52), (b) subplots within long borders (N=30), and (c) subplots within short borders (n=22) for the Wet (I_1) irrigation treatment.

Variable	Symbol	Units	Range	Mean	SD	CV (%)
(a) Grain Yield	Y	kg/ha	3487.5 to 6508.8	5192.8	635.8	12.2
Total Seasonal Irrigation Water Applied	Q	mm	502.5 to 700.7	573.7	36.2	6.3
Total Seasonal Gross Water Applied	GWA	mm	572.4 to 772.1	644.5	38.0	5.9
Measured Seasonal Soil Moisture Depletion	SMD	mm	484.2 to 667.0	565.3	45.1	8.0
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation	θ_p	m/m	0.101 to 0.219	0.178	0.027	15.2
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.171 to 0.289	0.253	0.026	10.3
Seasonal Average Volumetric Soil Moisture Contents	$\overline{\theta}$	m/m	0.137 to 0.254	0.217	0.027	12.4
(b) Grain Yield	Y	kg/ha	4112.8 to 6228.6	5292.1	531.7	10.0
Total Seasonal Water Applied	Q	mm	502.5 to 644.1	567.2	33.5	5.9
Total Seasonal Gross Water Applied	GWA	mm	572.4 to 702.4	638.0	36.9	5.8
Measured Seasonal Soil Moisture Depletion	SMD	mm	507.0 to 667.0	567.3	44.0	7.8
Average Volumetric Soil MoistureContents, 1 Day Prior to Irrigation	θ_p	m/m	0.111 to 0.217	0.179	0.024	13.4
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.190 to 0.288	0.254	0.023	9.1
Seasonal Average Volumetric Soil Moisture Contents	$\overline{\theta}$	m/m	0.150 to 0.254	0.218	0.024	11.0
(c) Grain Yield	Y	kg/ha	3487.5 to 6508.8	5057.4	747.1	14.8
Total Seasonal Water Applied	Q	mm	536.2 to 700.7	582.5	38.6	6.6
Total Seasonal Gross Water Applied	GWA	mm	600.4 to 772.1	653.4	38.4	5.9
Measured Seasonal Soil Moisture Depletion	SMD	mm	484.2 to 646.0	562.7	47.4	8.4
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation	θ_p	m/m	0.101 to 0.219	0.176	0.031	17.6
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.171 to 0.289	0.252	0.030	11.9
Seasonal Average Volumetric Soil Moisture Contents	$\overline{\theta}$	m/m	0.137 to 0.254	0.216	0.031	14.4

Table 4. Means, ranges, standard deviations (SD), and coefficient of variations (CV) of grain yield, total seasonal irrigation water applied, total seasonal gross water applied seasonal soil moisture depletion, average soil moisture contents 1 day prior to irrigation, average soil moisture contents 1 day prior to irrigation, and seasonal average soil moisture contents 3 days after irrigation, and seasonal average soil moisture for the Medium (I_2) irrigation treatment.

Variable	Symbol	Units	Range	Mean	SD	CV (%)
(a) Grain Yield	Y	kg/ha	2026.1 to 5657.1	3936.5	789.8	20.1
Total Seasonal Irrigation Water Applied	Q	mm	403.1 to 534.1	459.0	31.2	6.8
Total Seasonal Gross Water Applied	GWA	mm	465.0 to 636.0	546.0	41.1	7.5
Measured Seasonal Soil Moisture Depletion	SMD	mm	350.4 to 591.9	450.7	53.2	11.8
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation	θ_p	m/m	0.093 to 0.206	0.161	0.09	18.0
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.140 to 0.279	0.238	0.030	12.6
Seasonal Average Volumetric Soil Moisture Contents	$\bar{\theta}$	m/m	0.115 to 0.250	0.206	0.030	14.6
(b) Grain Yield	Y	kg/ha	2026.1 to 5657.1	3771.8	805.4	21.4
Total Seasonal Water Applied	Q	mm	404.6 to 508.5	455.4	24.5	5.4
Total Seasonal Gross Water Applied	GWA	mm	465.0 to 618.2	545.8	35.0	6.4
Measured Seasonal Soil Moisture Depletion	SMD	mm	356.0 to 517.5	447.4	40.0	8.9
Average Volumetric Soil MoistureContents, 1 Day Prior to Irrigation	θ_p	m/m	0.093 to 0.204	0.160	0.031	19.4
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.140 to 0.275	0.237	0.034	14.3
Seasonal Average Volumetric Soil Moisture Contents	$\bar{\theta}$	m/m	0.115 to 0.248	0.205	0.034	16.6
(c) Grain Yield	Y	kg/ha	2828.5 to 5466.6	4161.1	726.3	17.5
Total Seasonal Water Applied	Q	mm	403.1 to 534.1	463.8	38.7	8.3
Total Seasonal Gross Water Applied	GWA	mm	468.4 to 636.6	546.2	49.0	9.0
Measured Seasonal Soil Moisture Depletion	SMD	mm	350.4 to 591.9	455.3	68.0	14.9
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation	θ_p	m/m	0.115 to 0.206	0.161	0.027	16.8
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.197 to 0.279	0.240	0.023	9.6
Seasonal Average Volumetric Soil Moisture Contents	$\bar{\theta}$	m/m	0.164 to 0.250	0.208	0.025	12.0

Table 5. Means, ranges, standard deviations (SD), and coefficient of variations (CV) of grain yield, total seasonal irrigation water applied, total seasonal gross water applied seasonal soil moisture depletion, average soil moisture contents 1 day prior to irrigation, average soil moisture contents 1 day prior to irrigation, and seasonal average soil moisture contents 3 days after irrigation, and seasonal average soil moisture for the Dry (I_3) irrigation treatment.

Variable	Symbol	Units	Range	Mean	SD	CV (%)
(a) Grain Yield	Y	kg/ha	638.8 to 3514.4	1469.7	504.4	34.3
Total Seasonal Irrigation Water Applied	Q	mm	188.5 to 312.4	253.8	29.6	11.7
Total Seasonal Gross Water Applied	GWA	mm	273.3 to 447.1	360.7	42.1	11.7
Measured Seasonal Soil Moisture Depletion	SMD	mm	208.6 to 391.7	313.4	41.3	13.2
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation	θ_p	m/m	0.091 to 0.187	0.140	0.023	16.4
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.161 to 0.281	0.234	0.028	12.0
Seasonal Average Volumetric Soil Moisture Contents	$\bar{\theta}$	m/m	0.120 to 0.235	0.185	0.028	15.1
(b) Grain Yield	Y	kg/ha	786.7 to 3514.4	1527.5	579.3	37.9
Total Seasonal Water Applied	Q	mm	188.5 to 312.4	269.4	28.0	10.4
Total Seasonal Gross Water Applied	GWA	mm	285.7 to 447.1	380.1	40.6	11.3
Measured Seasonal Soil Moisture Depletion	SMD	mm	249.6 to 391.7	326.8	37.4	11.4
Average Volumetric Soil MoistureContents, 1 Day Prior to Irrigation	θ_p	m/m	0.097 to 0.183	0.143	0.022	15.4
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.616 to 0.281	0.240	0.026	10.8
Seasonal Average Volumetric Soil Moisture Contents	$\bar{\theta}$	m/m	0.127 to 0.232	0.187	0.024	12.8
(c) Grain Yield	Y	kg/ha	638.8 to 2030.3	1390.9	378.3	27.2
Total Seasonal Water Applied	Q	mm	204.8 to 262.1	232.4	14.8	6.4
Total Seasonal Gross Water Applied	GWA	mm	273.3 to 384.3	334.2	27.5	8.2
Measured Seasonal Soil Moisture Depletion	SMD	mm	208.6 to 369.9	295.2	40.0	13.6
Average Volumetric Soil Moisture Contents, 1 Day Prior to Irrigation	θ_p	m/m	0.091 to 0.187	0.137	0.026	19.0
Average Volumetric Soil Moisture Contents, 3 Days After Irrigation	θ_a	m/m	0.165 to 0.274	0.226	0.028	12.4
Seasonal Average Volumetric Soil Moisture Contents	$\bar{\theta}$	m/m	0.120 to 0.235	0.183	0.033	18.0

Table 6. Correlation coefficients (r) of seasonal irrigation water applied (Q), seasonal gross water applied (GWA), seasonal soil moisture depletion (SMD), seasonal average soil moisture contents (θ), seasonal average soil moisture contents for 1 day prior to irrigation (θ_p), and 3 days after irrigation (θ_a), and grain yield (Y) for all subplots within the Wet, Medium, and Dry irrigation treatments (n=52).

Irrigation Treatment		Q	GWA	SMD	θ_p	θ_a	$\bar{\theta}$
Wet (I_1)	Y	-0.29*	-0.20	0.23	0.51*	0.52*	0.50*
	Q		0.91*	0.35*	-0.50*	-0.40*	-0.46*
	GWA			0.59*	-0.42*	-0.29*	-0.38*
	SMD				-0.15	-0.09	-0.10
Medium (I_2)	Y	0.44*	0.49*	0.59*	0.36*	0.49*	0.43*
	Q		0.96*	0.88*	0.17	0.06	-0.06
	GWA			0.90*	-0.06	0.16	0.05
	SMD				-0.08	0.17	0.06
Dry (I_3	Y	0.25	0.46*	0.36*	0.49*	0.43*	0.46*
	Q		0.90*	0.78*	0.19	0.53*	0.22
	GWA			0.84*	0.34*	0.61*	0.39*
	SMD				0.06	0.43*	0.11

* Significant correlation at $P < 0.05$

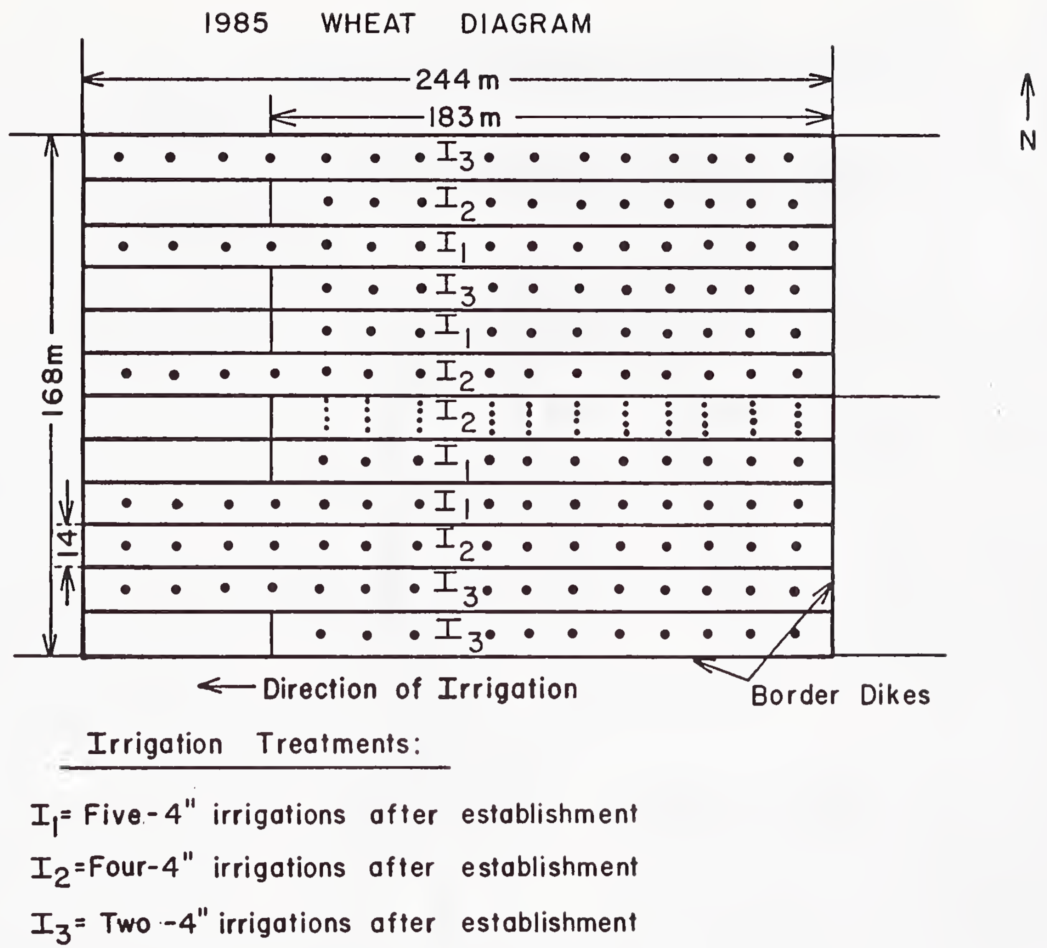

Figure 1. Field plot diagram showing irrigation treatments, border lengths, and location of neutron access tubes (dark circles) for wheat planted in January, 1985, at the Maricopa Agricultural Center, near Maricopa, AZ.

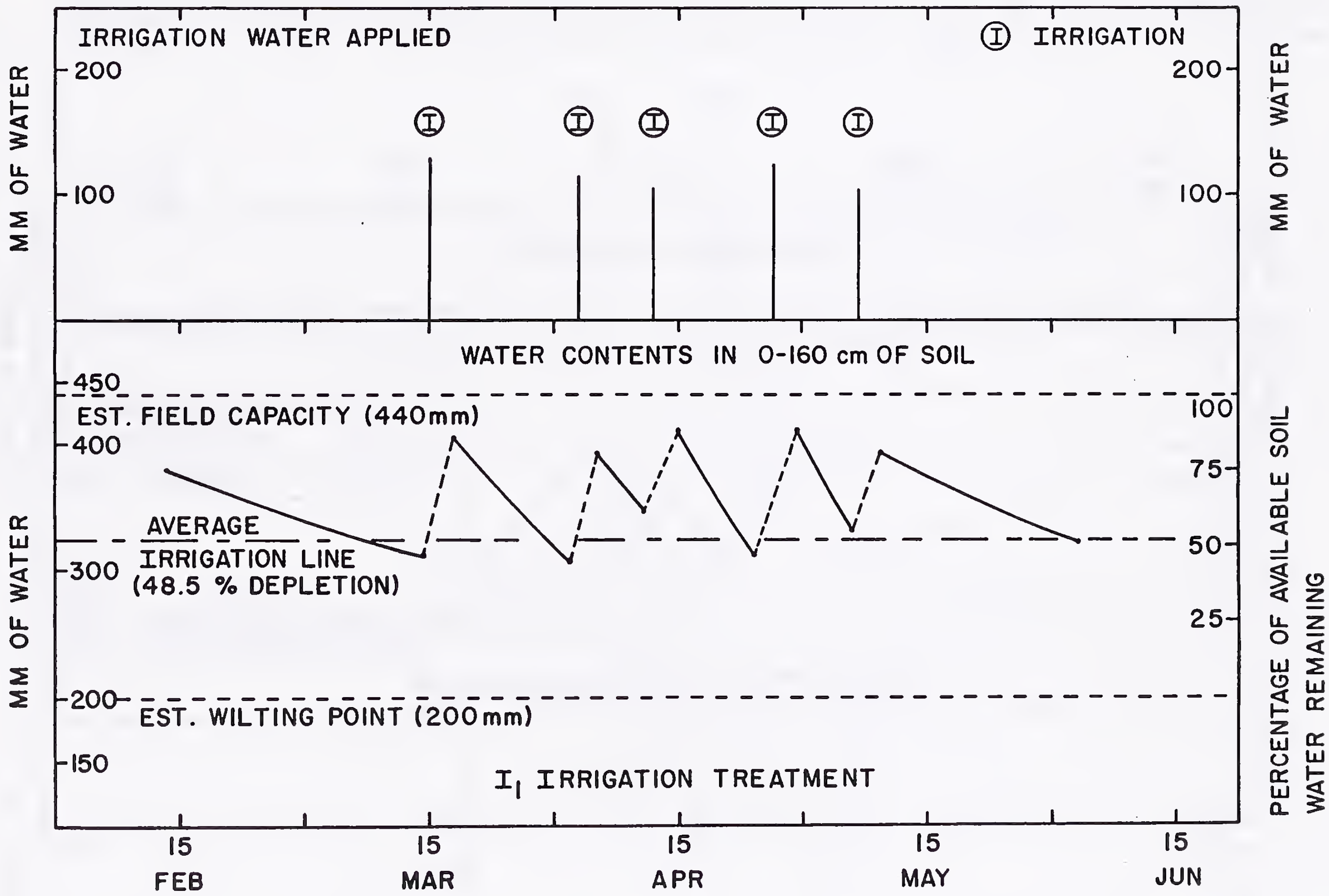

Figure 2. The average irrigation water applied and soil water contents for the Wet (I_1) irrigation treatment at the Maricopa Agricultural Center, near Maricopa, AZ, 1985. (Five irrigations were given after 48.5% of the available soil water was depleted in the 0-160-cm depth).

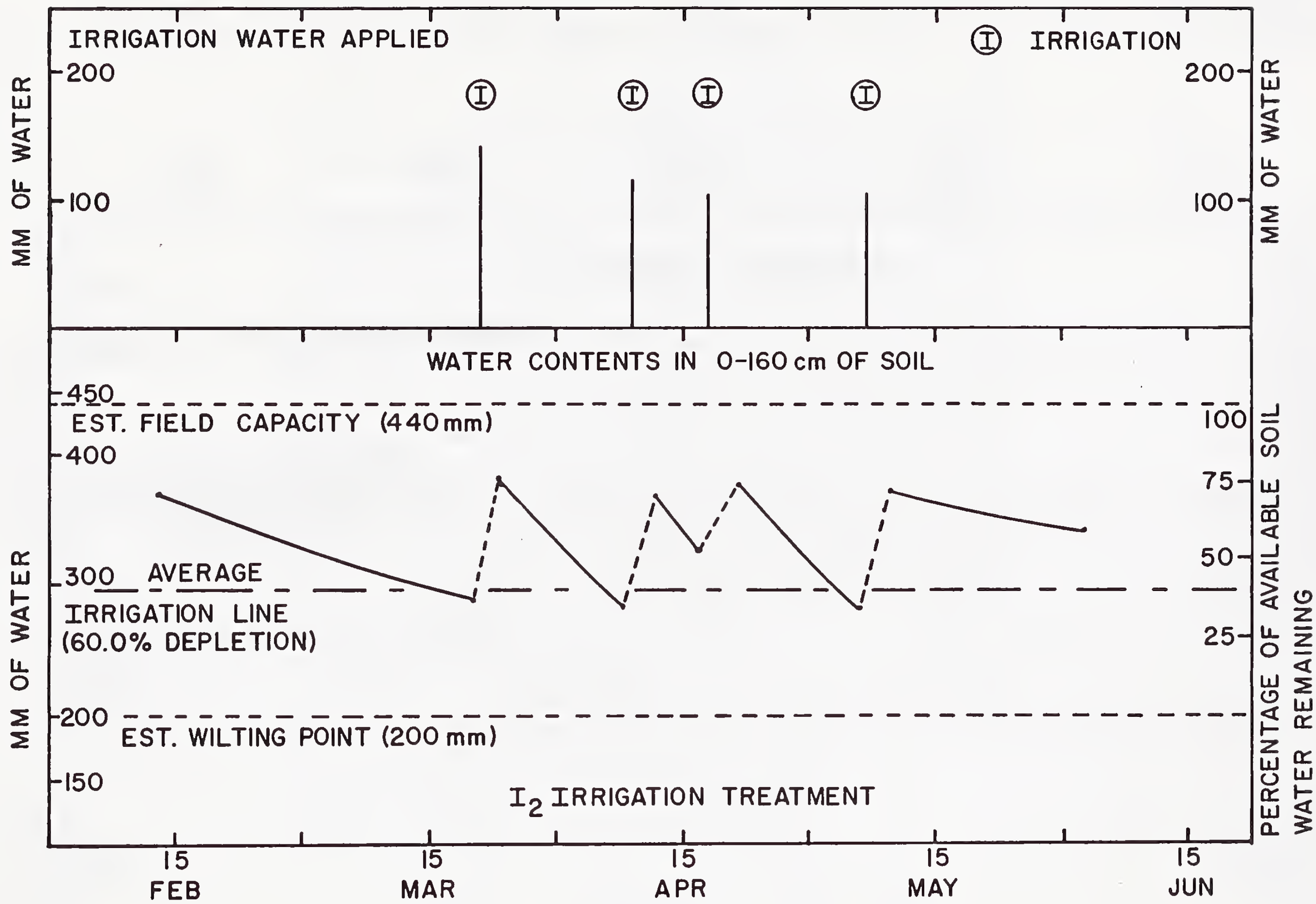

Figure 3. The average irrigation water applied and soil water contents for the Medium (I_2) irrigation treatment at the Maricopa Agricultural Center, near Maricopa, AZ, 1985. (Four irrigations were given after 60.0% of the available soil water was depleted in the 0-160-cm depth).

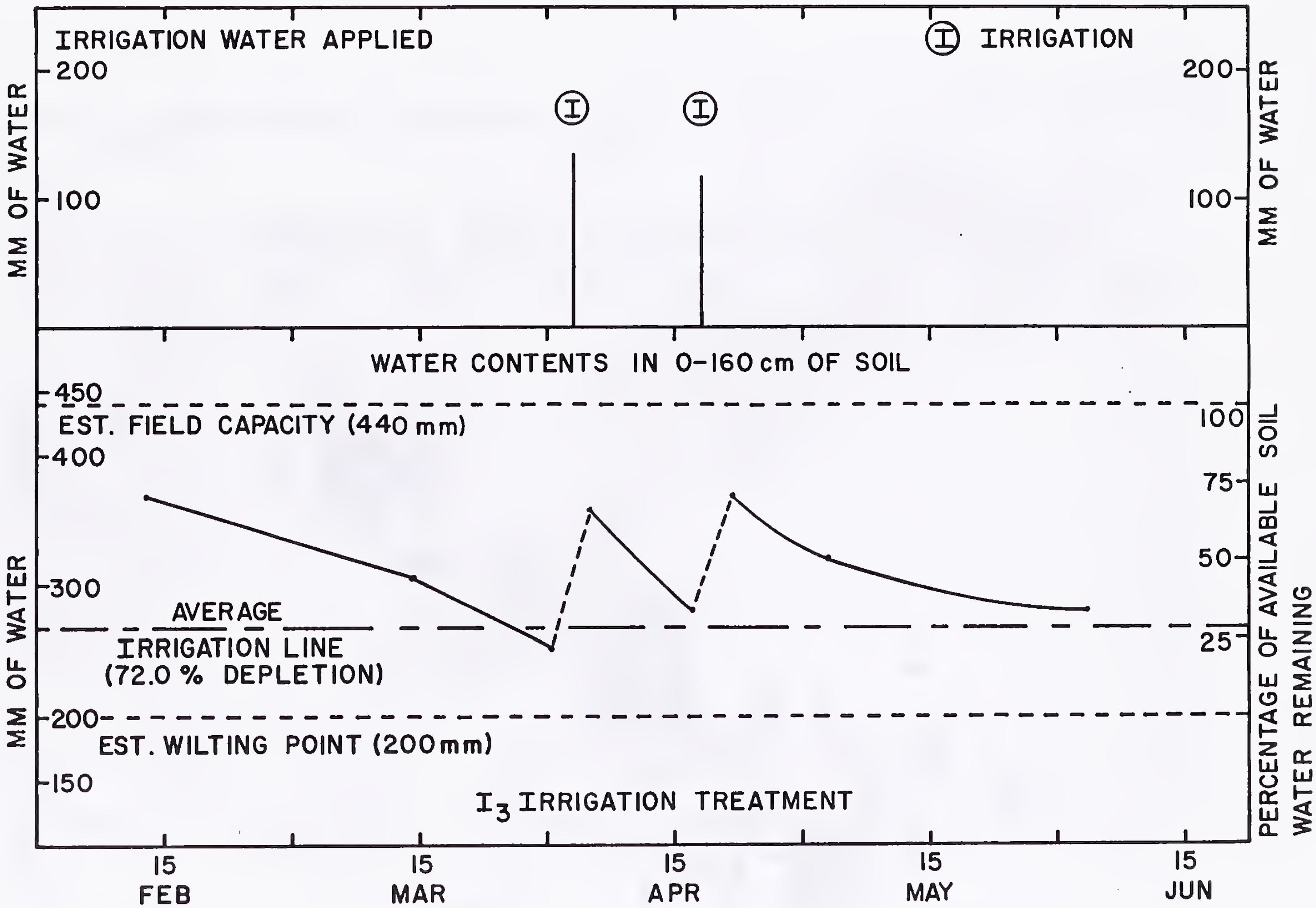

Figure 4. The average irrigation water applied and soil water contents for the Dry (I_3) irrigation treatment at the Maricopa Agricultural Center, near Maricopa, AZ, 1985. (Two irrigations were given after 72.0% of the available soil water was depleted in the 0-160-cm depth).

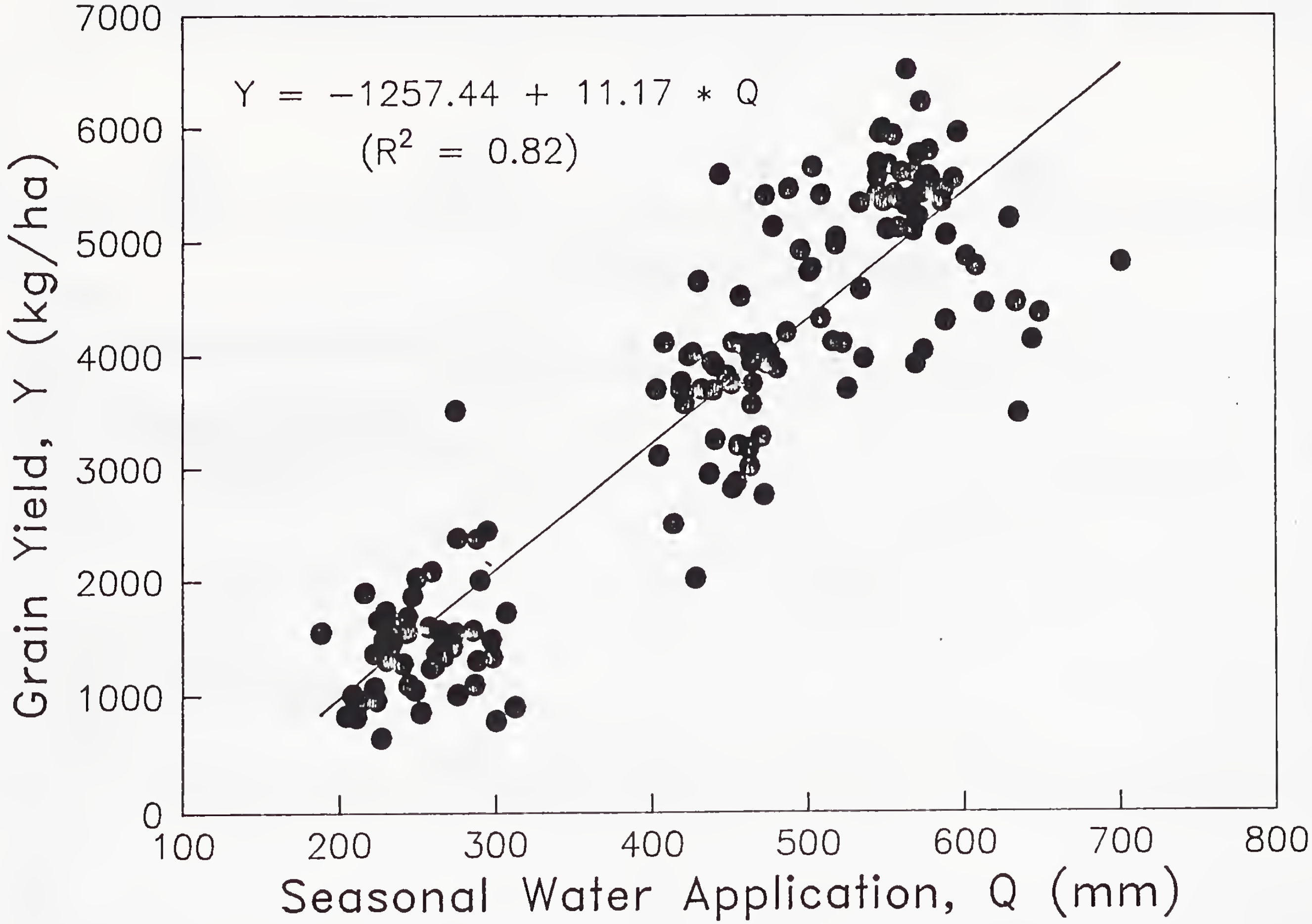

Figure 5. Grain yield as a function of seasonal water application, all subplots; 1985.

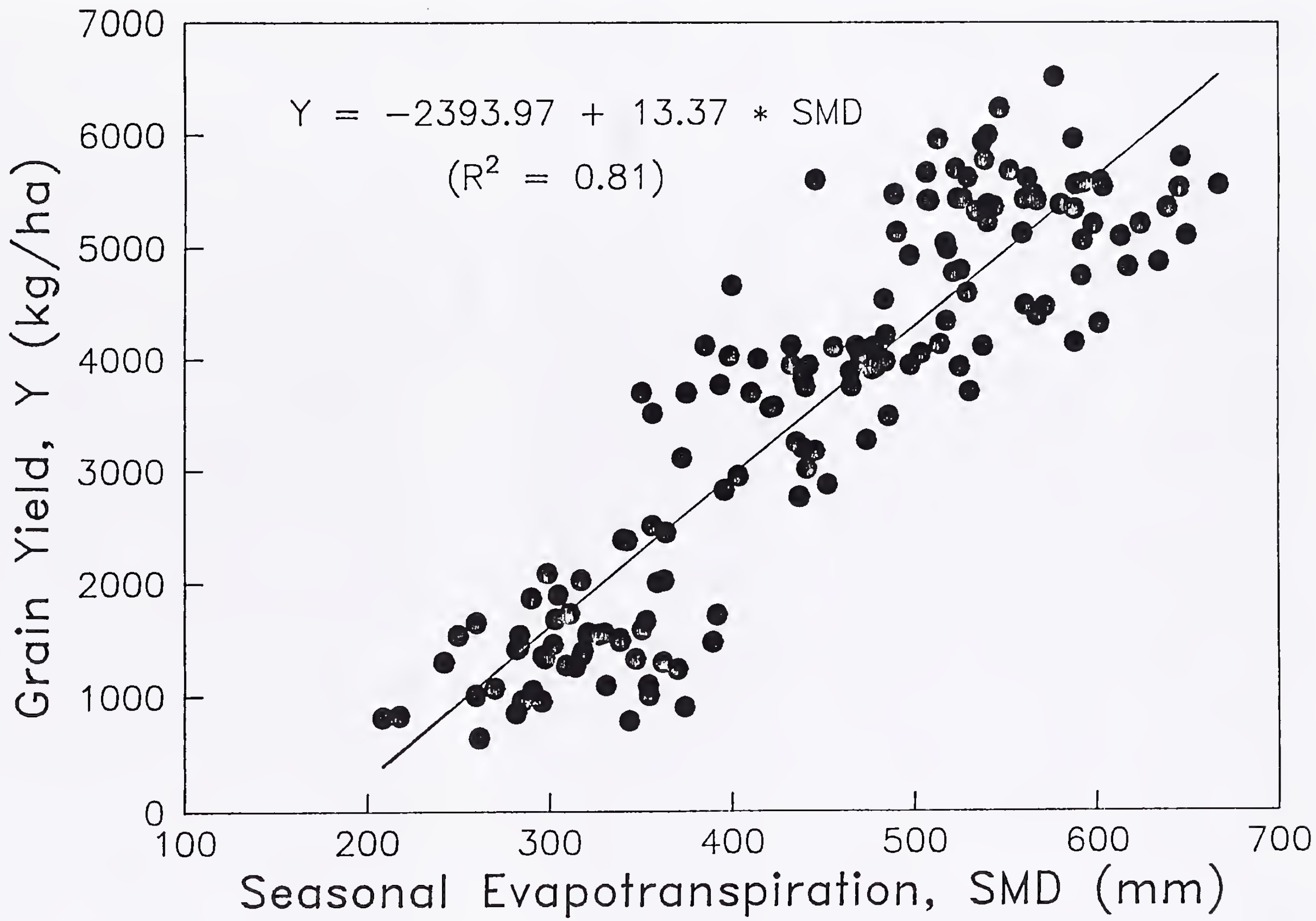

Figure 6. Grain yield as a function of seasonal evapotranspiration, all subplots; 1985.

TITLE: MECHANIZATION OF LEVEL-BASIN SYSTEMS

NRP: 20740 CRIS WORK UNIT: 5510-20740-004

INTRODUCTION

Work on the the mechanization of level-basin systems continued during 1985. At the request of the Soil Conservation Service (SCS) we developed two mechanized level-basin systems for farms in the Wellton-Mohawk Irrigation and Drainage District (WMIDD). Both were part of the on-farm irrigation improvement program administered by the SCS in the Wellton--Mohawk project, Table 1. This brings to eight the number of systems that have been designed and installed in the project since 1975. The first two systems were research and demonstration type systems installed at the request of the Agricultural Research Service. The last six, including one installed late in 1985 and one installed in early 1986, were operational systems used on-farm and cost-shared by the Soil Conservation Service. The latest systems included the largest acreages (231 and 169 acres) of any yet. The 231 acre system was installed in October-November 1985, while the 169 acre field was completed in January 1986. Design and installation information for these systems is included in this report.

Electrical/mechanical controllers originally used on the McElhaney-McDonnell #1 mechnaized system were replaced with electronic controllers in 1982. The electronic controllers provided a digital display of time remaining on a particular station, exact timing of an irrigation, and a means of interfacing equipment for volumetric control of water applied. Some damage to the electronic controllers in 1984 along with the controllers not being particularly user friendly resulted in our converting this control center back to something near the original, again featuring the original electrical/mechanical controlling device.

RESULTS AND DISCUSSION

The mechanized systems designed during 1985 required that the systems be reliable from the operators standpoint. In an effort to achieve this reliability electrical/mechanical controllers were used that have a history of operating successfully in the field for extended periods. Further, these controllers are inherently simpler to program than most electronic controllers, thereby more easily used by the irrigator/operator. Although the electrical/mechanical controllers are more reliable they are however, not as accurate or precise as electronic controllers. Each station time on the mechanical controller is controlled by the setting of a station timing knob. The resultant accuracy is dependent on both proper calibration/adjustment of the knob and the ability of the user to set the knob properly. The average standard deviation of 17 stations repeating from irrigation to irrigation (knobs not reset) was 2.8 minutes, when the stations were set at about 75 minutes. Initial station timing knob calibration (how accurately the controller reproduces the time setting indicated) requires four or five repetitions in adjusting and testing.

To test the ability of a user to set a station timer and repeat the results of previous runs was done by having three persons set a controller independently three different times. After each setting the controller was allowed to run through its cycle. Time was recorded for each controller station. Again 17 stations were used. Interestingly the variation from setting to setting (knobs reset) for the three operators was either about the same or less than when the knobs were not reset (average standard deviations were 3.2, 1.7, and 1.7 for the three operators). This repeatability is acceptable, especially since the average station setting on the 231 acre farm will be four hours or more and over two hours on the 169 acre farm.

New Hoffman Enterprise Systems: The 231 acre field (HE #3) is divided into 18 basins with water supplied in a concrete lined canal as shown in Figure 1. The 169 acre field (HE #4) is divided into 14 basins supplied from one district turnout and 2 basins from another district turnout, Figure 2. Shallow soils prevented cutting basins 15 and 16 so they could be irrigated from the same water supply. The engineering design of the level-basin systems was done by the SCS. Flow rate from the Wellton-Mohawk Irrigation and Drainage District averages about 16 ft^3/s for HE #3 and 20 ft^3/s for HE #4. The control centers are located near 115 VAC power.

Gate Modification

Procedures for adapting air cylinders to lift gates were standardized a number of years ago. The modification features bolting the cylinder to an angle iron welded to the gate and a connector between the cylinder rod and rod normally used to manually open the gate. Four and one half inch bore cylinders were used. All gates, except checks 1 and 2 and basins 13, 14, and 15 of HE #3 were equipped with 18 inch stroke cylinders. Longer cylinders were used on these five gates to minimize head losses into basins 13, 14, and 15 and eliminate any restriction in flow from the irrigation district canal. The longer cylinders were those originally installed on the Woodhouse mechanized system in 1976 and removed in 1984. These 4½ inch bore cylinders have a 33 inch stroke. They were mounted on the gates to provide 28 inch gate travel. As a precautionary measure the U-cup seals were replaced, even though the air operated cylinders were essentially air tight.

On-farm control of the water supply from the Irrigation District is institutionally impossible at the present time. Hence, in case of a power failure (electrical or pneumatic) the incoming water must be controlled on-farm. This is done by routing the incoming water to a designated basin (generally lowest lying basin). This path is produced by having certain gates operating as normally open (signal and valving adapted to provide open gate when not signalled). Field gates are normally closed. In both systems the path was created by having checks 1, 2, 3, and 4 normally open (gate to basin 18 for HE #3 and to basin 14 for HE #4). The gate to basin 16 of HE #4 was operated as a normally open gate. Helical springs are added to the cylinder/gate modification package to effect the normally open mode in cases of air loss. The helical springs were the same design as those used on earlier Hoffman systems in 1979.

However, they were mounted externally rather than internally as had been done in the earlier systems. A bracket, pipe, and threaded stock were used to adapt the spring to the gate. Closure force developed by the cylinder and operated at 50 psi is about 800 lbs. Lifting force of the spring at 18 inch displacement is about 500 lbs. The springs open the gate about 12 to 13 inches. Specifications for the springs are:

SPRING FACTOR (K):	28 lbs/in
MATERIAL:	17-7 stainless steel
WIRE DIAMETER:	0.225 in.
SPRING ID:	1.300 in
COILS:	total 35
	active 33
FREE LENGTH:	27 to 28 in.
MAXIMUM SOLID LENGTH:	7.88 in

Cylinders are purchased with 8 inches of rod extending outside the cylinder to accommodate canvas sleeves. Two inch nominal diameter canvas sleeves are used to protect the cylinder rods from fouling. The procedure was first used on cylinders in the Wellton-Mohawk project in 1979 and has provided the protection needed.

Gate Signalling and Actuation

We have options of using either electric or pneumatic signals from the controller to the gates. Three of the earlier mechanized systems in the WMIDD utilized pneumatic signals and performed very well. Pneumatic signals do, however, cause delays in gate actuation. The amount of delay, both in opening (tube pressurization) and closing (tube depressurization), depends on the tubing diameter, characteristics of the four-way valve, pilot line operating pressure, and distance to the valve. The time for gates to open and close for distances up to 4,000 feet for three air pressures is shown in Figure 3. The following can be seen from the illustration a) higher signal pressures, cause gates to open quicker, but close slower, b) whether a gates opens before a gate at the same distance from the control center closes depends on the signal pressure (at 40 psi the gate would close before another would open but at 45 psi it would open first), c) the delay in closure can be controlled by the inlet pressure and d) gate actuation delay for a 45 psi signal pressure exceeds three minutes at a distance of 3,300 ft from the control center (distance to farthest gate in HE #3 system) and would approach 4 minutes at 3,700 ft (farthest distance at HE #4). These delay periods are inconvenient when operating the system, hence electric signals were selected over pneumatic mainly to eliminate these delay problems. In addition, multiple conductor cable (22 gauge conductors) was easier to install than multiple polyethylene tubes and 22 gauge wire is less costly than polyethylene tubing.

Relays (3PDT) were located at each gate to switch 24 VDC power to solenoid actuated three-way valves; to provide check gate signals; and overflow gate actuation, Figures 4 and 5. Three-way valves served as a pilot for a larger four-way valve used to divert compressed air to either the bottom of the air cylinder to open the gate or top of the cylinder for closure. Twenty-four VDC power was supplied by a pair of 14 gauge wires daisychained to all gates. Twenty-two gauge wire, wired directly from the control center to each gate (relay), was used to signal gate actuation. Unshielded, multiple conductor, color coded, vinyl jacketed electrical cable was used.

An added feature of the system is an electrical feedback to the control center from the basin gates. This feedback provides a positive indication of gate opening (or closing). The feedback, produced by the actuation of an electrical switch when a gate opens (basin gate) or closes (check gate), powers indicator lights on a control panel. The feature assures the irrigator that the gate or gates have indeed actuated. Such a feature is especially useful if checking the system at night or doing a quick checkout before an irrigation starts. Power for the feedback is supplied from the daisychained pair.

The gate relay, three-way and four-way valves, and electrical switch for feedback (wobble switch) are enclosed in or attached to a metal knockout enclosure attached to the gate. The electrical and pneumatic hookup at each gate is shown schematically in Figures 4 and 5 for basin and checkgates, respectively. Gate override (open a normally closed field gate or close a normally open checkgate) is accomplished by using a quick disconnect on the wire from the relay coil to the +24 VDC of the daisy chained pair. Further, the signal to the gate can be interrupted by disconnecting the wire normally connected to the relay.

The system is protected from canal overflow by stationing float sensors along the canal, Figures 1 and 2. If the canal water level exceeds a normally expected level, a signal from the float switch is sent to each basin gate and checkgate. This signal can be used to actuate the three-way valve and open the gate, if the wire leading from the terminal strip to the relay is connected. Hence a gate is designated to handle an overflow by attaching the wire. Otherwise, the gate is not affected by the overflow signal.

Compressed air is supplied to the cylinders and 3-way valves through polyethylene tubing from an air compressor located at the control center. Three 5/16 inch OD x 3/16 inch ID polyethylene tubes are used to supply air to the cylinders. One 1/4 inch OD x 1/8 ID polyethylene tube is used to the three-way valves.

All electrical wire (pair of 14 gauge and multiple conductor 22 gauge cable) and polyethylene tubes must be protected from various forms of mechanical damage and vermin, especially gophers prevalent in the area. This protection is attained by encasing the tubes and wire in 1½ rigid PVC pipe. The encased wire and tubing is then buried in a trench, next to the concrete lined canal, at a depth of about 1 foot. The wire and

tubing were carried in flexible PVC from the rigid PVC, exposed at the turnout structures, to the enclosures mounted on the gates. The use of flexible PVC in this application is untested. The flexible PVC was coated with an elastomer lacquer, Elastuff 400 from United Coatings, to provide protection from UV attack. The coating material has performed exceptionally well when tested previously on rigid PVC pipe and flexible PVC film. In addition to UV degradation, the exposed pipe can potentially be damaged by vandals and weed burning near the gate turnouts. The flexible PVC did, however, facilitate installation and results in a clean looking installation.

Control Center

Sheds constructed by the farmer/cooperator were used for the control centers, Figures 1 and 2. Electrical power was supplied to the control center for operating the air compressor, controller, and control panel. The control center featured an electrical/mechanical controller, irrigation sequencing capabilities, a display panel with indicator lights, battery backup system, battery charging capability, remote or autostart, and a timer to show elapsed time that a gate has been open.

Automatic Timer: The system used was a Toro, 23 station, pedestal mounted controller. The timing device is electrical/mechanical, which actuates an electrical switch. Time settings are independently adjusted on each of the 23 stations for periods up to 9 hours. Accuracy and precision of the time setting were discussed earlier.

Output from the controller is normally 24 VAC. To accomodate DC powered solenoids the controller was modified by a) replacing the standard transformer with a 4 amp, 24 VAC transformer and b) adding a rectifier, capacitor, and potentiometer. The rectified output provided power for both signaling and daisychained power to all gates as discussed earlier. The potentiometer allowed output voltage adjustment to accommodate different field layouts.

Sequence Selection: The controller advances through the stations in sequence from 1 through 23. To provide random sequencing of how the basins are irrigated a matrix board was used and has been described in earlier reports. Output from the controller is input to the board. Output from the matrix board to the desired basin is selected by pinning the board as required. In addition, the gates can be operated manually (if the controller should malfunction) by pinning the desired basin on a row of the matrix marked MANUAL. The MANUAL matrix row is continually powered by 24 volt VDC input from the batteries used for backup.

As noted earlier, the on-farm irrigation function and the irrigation district turnout are independent and are operated by different people. It is likely that the water would not be stopped from the district at the same time that the irrigation controller automatically closed the last gate. This excess water is directed into basins selected by the irrigator by properly pinning a row on the matric called RUNDOWN. The RUNDOWN row is powered by the 19^{th} controller station for HE #3 and the 17^{th} station for HE #4.

Display Panel: A display panel made up of a schematic layout of the basins was included as an operator aid, partially described earlier. Two panel indicator lights are used for each basin (two different colors). The first indicates a signal is being sent to a basin and the second indicates a gate has actuated (assured actuation via the gate sensor switch--wobble switch). A lighted return light indicates that a basin gate has opened or that a check gate has closed.

Battery Backup: Intermittent power outages may cause electronic based controllers to loose the program times and without battery backup field signaling is lost. In contrast, electrical/mechanical controllers, because of their mechanical characteristics, stay in the station or position they were in when the power outage occurred. Once power is restored the controller continues where it left off. Water would be applied in excess of what was expected and would be proportional to the time the controller was off. In most instances the amount of excess water applied is small and it is likely that the irrigator or farmer is unaware that a power outage occurred.

A set of three relays were used to provide battery backup in case of 115 VAC power failure, Figure 6. When AC power is lost, the 24 VDC battery system is switched on line to provide both the signal and daisychained power to all gates. When AC power is available, all output to the field is supplied by the rectified AC from the controller. The battery system is being charged while irrigating.

Autostart: The systems are remotely started by actuating the first overflow float switch of each system, Figures 1 and 2. The controller requires a switch closure so that the timer can mechanically move to station #1 when the field canal above checkgate #1 is nearly full. Two relays located on the control panel were used to provide the remote start, Figure 7. Since checkgates are normally open, the first checkgate must be closed to effect an overflow. The remote start is set by pressing a push button, spring return switch on the control panel. This actuates relay #5, Figure 7, which closes checkgate #1. Once an overflow is sensed relay #6 is activated which cancels relay #5 and provides the switch closure to start the controller. When the overflow cancels relay #6 is released.

Station Timer: As an additional operator aid a digital clock was added to the system. The clock is used to indicate the lapsed time that a basin has been irrigating. The clock is reset and started using a relay signalled by the electrical feedback from the gate opening, Figure 8. An 115 VAC clock (alarm clock in this case) with LED numerals was used. The clock resets to 12 o'clock if power is lost. When a station change is made, the open gate closes before the next gate opens. Hence there is a period of time when there is no signal to the relay and AC power is lost, resetting the clock. Once the next gate opens the power to the relay and clock is restored. Diodes are used to isolate the feedback signals.

Equipment Assembly, Field Installation, and System Costs

Much assembly of equipment was done in the shop and laboratory before installing in the field. This included electrical wiring of the control center; gate enclosure panels; and mounting of valves, relays, etc. for the gate boxes. Five experienced persons are needed to lead the installation in the field. These personnel, supplied from this laboratory, were involved in laying out electrical wire and polyethylene tubing, encasing the wire and tubing in PVC, mounting enclosures on gates, installing the equipment in the control center, installing electrical conduit, and doing all electrical wiring and polyethylene tubing hookup. The field time for these persons per system was about 8 days or 320 man-hours, Table 2.

The farmer/cooperator supplied three or four laborers to assist in encasing the wire and tubing. In addition the farmer adapted the cylinders to the gates (one welder and helper, 1.5 hour per gate); installed overflows (2 persons, 2 hours per overflow); trenched for receiving PVC pipe, Table 2; and did necessary grouting around the concrete turnout structures. A tractor and blade, used to construct the trench on the second system in January 1986 was about four times as fast as the walking trencher, Table 2. Wire and tubing were unspooled from a bracket on the back of a truck on HE #4 at about 750 ft per hour. This was done by a four-man crew and included one or two multiple conductor (22 gauge) electrical cables, two 14 gauge wires, and four polyethylene tubes. On the first system the spools were fixed at the end of the canal and the tubing or wire was unspooled by walking. Slowness of this procedure is a problem; but more seriously the tubing, jacketing, or insulation can be damaged when dragged.

Hardware costs for each system were about $16,000. This yields unit costs for hardware of about $70 per acre or $770 per gate for HE #3 and $95 per acre or $845 per gate for HE #4. Labor costs for each system were estimated to be between $50 and $70 per acre.

McDonnell-McElhaney #1 (MM #1)

An electrical/mechanical controller originally used on this system (1977) was replaced by a pair of electronic controller in 1982. The objectives of using the electronic control were to be more precise in programming (digital display rather than knob) and to provide volumetric control. Although the controllers fulfilled these objectives, the problems with their use were serious. Problems encountered could generally be attributed to lightning damage, power outages, and/or programmer error.

Lightning - Various components associated with electronic irrigation controllers and a DC power supply were damaged by lightning at another McDonnell-McElhaney mechanized system (MM #2) during 1984. The damage occurred five times. Each failure created a system shutdown and required maintenance after each. In most instances the failures were in the controller indicating a power surge on the 115 VAC incoming line. In at least one instance components in a DC

power supply providing power to the field failed suggesting a power surge from the field caused by a strike at the gates or in the immediate vicinity of the control center. In contrast to the electronic controllers, electrical/mechanical controllers used over a number of years have not been affected by these type problems. This would suggest that the electrical/mechanical are not as susceptible to damage by lightning.

Power Outages - Intermittent power outages may cause electronic based controllers to loose the program times and without battery backup field signaling is lost. In contrast, electrical/mechanical controllers, because of their mechanical characteristics, stay in the station or position they were in when the power outage occurred. Once power is restored the controller continues from where it left off. Water would be applied in excess of what was expected and would be proportional to the time the controller was off. In most instances the amount of excess water applied is small and it is likely that the irrigator or farmer is unaware that a power outage occurred. For example the MM #1 system was operated without incident from 1977 through 1980 for a total of about 100 irrigations. Certainly during this period of time some power outages would have occurred.

Programmer Error - Generally the electrical/mechanical controllers are easier to use than electronic controllers, since each station is represented by an individual dial. Once set the program time cannot be lost by power failure, etc. since the dial is a mechanical device. The electrical/mechanical controllers, however, are not as accurate as electronic controllers, as discussed previously.

The original electrical/mechanical controller was reinstalled on the MM #1 system in April 1985 in an effort to regain system reliability and more importantly to simplify the programming for the user. The mechanized system was part of a field day (tour) sponsored by the Extension Service and two Conservation Districts. The system was successfully used the rest of 1985.

The sequence by which basins were irrigated was selectable in the original control center design. This was achieved by using air tube quick disconnects. In the reinstallation, however, the farmer/cooperator optioned to fix the sequence.

Polyethylene tubing, originally used to power and signal gates across the canal from where the tubing was encased, was replaced with copper tubing in 1985. Copper was tried in an effort to attain more durability. The copper, although working satisfactorily through the irrigation season, was destroyed by sheep when the alfalfa was grazed in December. All tubing will necessarily be replaced in order to return to operational status.

SUMMARY

At the request of the Soil Conservation Service, we have designed and assisted in the installation, operation, and maintenance of six cost-shared mechanized level-basin systems in the Wellton-Mohawk Irrigation and Drainage District. The fields mechanized ranged from 64 to 231 acres in size while the number of basins within the fields ranged from 8 to 23.

Any problems that have been encountered at the control center of the mechanized irrigation systems can generally be attributed to lightning, power surges, power outages, and/or programmer error. Most problems outside the control center have been caused by either burning (common farmer practice is to burn the grass and weeds on the canal bank) or mechanical damage to exposed tubing (plastic or copper).

An electrical/mechanical controller originally used on one of the mechanized systems installed in 1977 was replaced by electronic controllers in 1982. The original electrical/mechanical controller was reinstalled in 1985 in an effort to regain system reliability and simplicity of operation. In addition two new mechanized level-basin systems were designed in 1985 with electrical/mechanical rather than electronic controllers. An added feature of these new systems is an electrical feedback to the control center from the basin gates. This feedback provides a positive indication of gate opening (or closing). The feedback powers indicator lights on a control panel. The feature will assure the irrigator that the gate or gates have indeed actuated. Such a feature is especially useful if checking the system at night or doing a quick checkout before an irrigation starts.

The problems resulting from lightning damage to the electronic controllers have been found because we have been operating these systems in the field under actual farming conditions. These observations played an important role in the final design of the two new systems that went into the Wellton-Mohawk Irrigation and Drainage District during 1985. Our primary goal is to look at water conservation but at the same time we must not sacrifice utility as far as the operator is concerned. Hence we are dealing with a tradeoff in which the indicators said that we should be going for a more reliable type controller that is easier to operate by the user than the electronic controllers tried in the early 1980's. The problems associated with lightning and electronic controllers no doubt can be solved, but is likely not our responsibility. Some contact has been made with the controller supplier and they have shown an interest in trying to investigate further the problems that we have seen.

Power failure or interruptions are especially critical when controlling on-farm mechanized gates since we do not have control of the open channel water supply coming from the irrigation district. In contrast such a controller in a turf application would have control of the water supply (valve or pump) and would automatically turn the water supply off if a failure (lightning damage) occurred. Since we cannot control the delivery point leads to the need to build in on-farm downstream safety equipment.

Electronic controllers are not particularly user-friendly. In most instances the controllers for level-basins would only be used 10 to 25 times a year. If the user does not totally understand the controller, reprogramming for an irrigation may be difficult for the user and will either lead to programming errors or non-use.

PERSONNEL

A.R. Dedrick, R.J. Gerard, J. Padilla, D.E. Pettit

Table 1. Automated irrigation systems in Wellton-Mohawk Irrigation and Drainage District

Year Installed	Owner/Operator	Acres	Number of Basins	Number of Checkgates	Number of Overflows
1975 1/	Woodhouse	65	8	1	2
	Naquin 2/	70	8	3	3
1977	McElhaney & McDonnell #1	64	23	2	4
1979	Joe Hoffman #1	110	8	2	3
	Hoffman Enterprises #1	80	12	1	2
1980	McElhaney & McDonnell #2	76	9 3/	4	5
1985	Hoffman Enterprises #3	231	18 3/	3	4
	Hoffman Enterprises #4 4/	169	16 3/	3	5
		865	102	19	28

1/ Research/Demonstration at USDA-ARS request, all others were operational systems, cost shared by the SCS.

2/ Automated ports--all others were lift-gates.

3/ One gate acts both as a basin gate and check gate.

4/ Installed in January 1986.

Table 2. Time and manpower required for installing electrical wire and tubing associated with mechanized level-basin systems.

Job	System HE #3	System HE #4
Trenching, Approx 12" deep	Walking Trencher	Tractor & Blade
Crew Size	1	1
Distance Trenched, ft	4,000	4,600
Time, hrs	22	6
Rate, ft/hr	180	760
Unspooling Wire & Tubing		
Crew Size		4
Distance, ft		4,600
Time, hrs (man-hrs)		6 (24)
Rate, ft/hr (ft/man-hr)		760 (190)
Encasing[1/]		
Crew Size		7
Distance, ft		3,000
Time, hrs (man-hrs)[2/]		7.5 (52.5)
Rate, ft/hr (ft/man-hr)[2/]		400 (55)
Crew Size		7
Distance, ft		1,500
Time, hrs (man-hrs)[3/]		3 (21)
Rate, ft/hr (ft/man-hr)[3/]		500 (70)

1/ 40-ft lengths of PVC pipe walked on the wire and tubing which had been unreeled and laid in the canal. All joints were solvent welded. Gate enclosures, flexible tubing, and various 45° elbows used at each gate were also walked on to the wire and tubing.

2/ Included seven gate enclosures walked on.

3/ Includes one gate enclosure mounted at terminal gate.

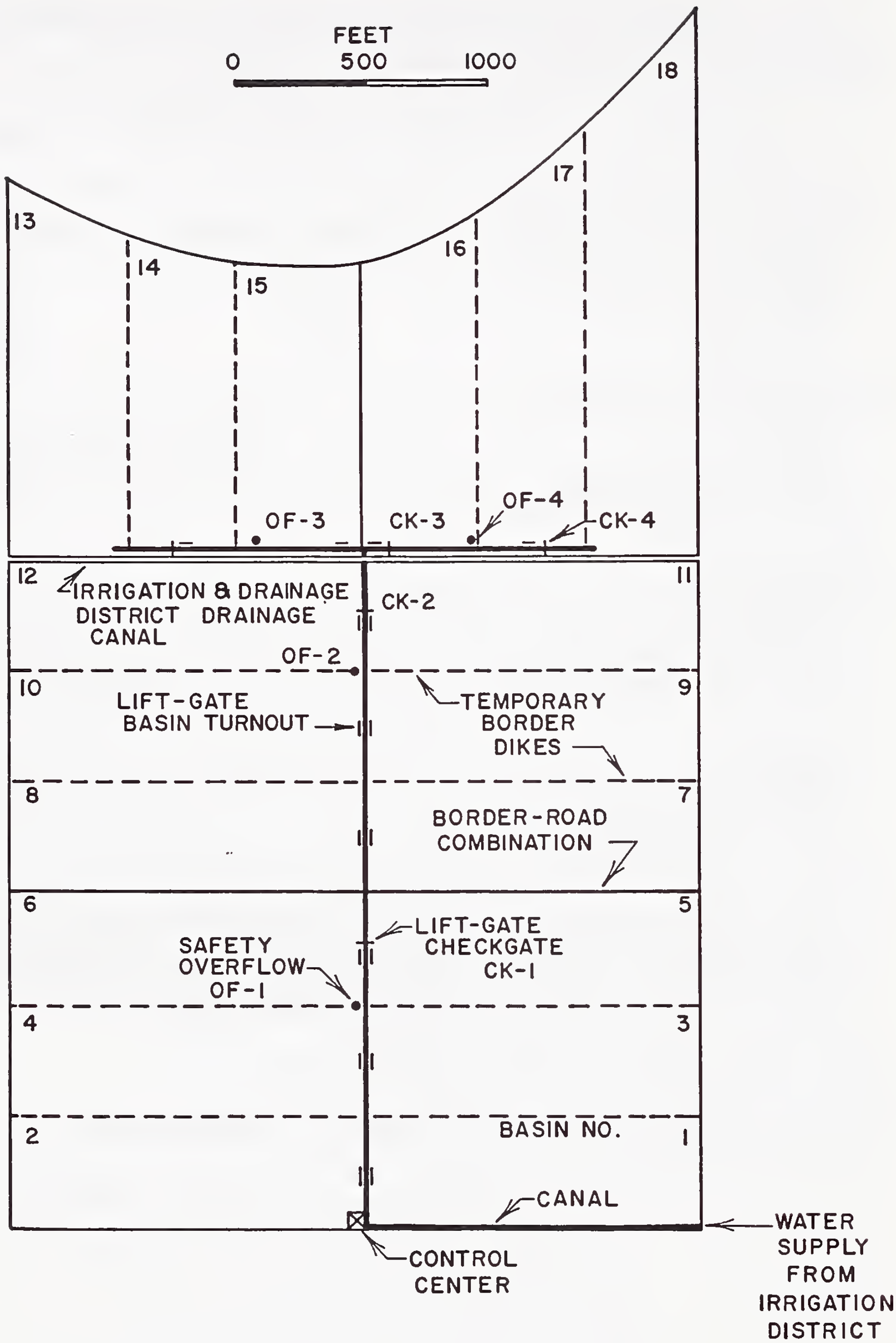

Figure 1. Field layout for 231 acre mechanized level-basin system on Hoffman Farm (HE #3) located in the Wellton-Mohawk Irrigation and Drainage District. Water is delivered from the Irrigation and Drainage District at about 16 ft^3/s. The system was installed in October-November 1985.

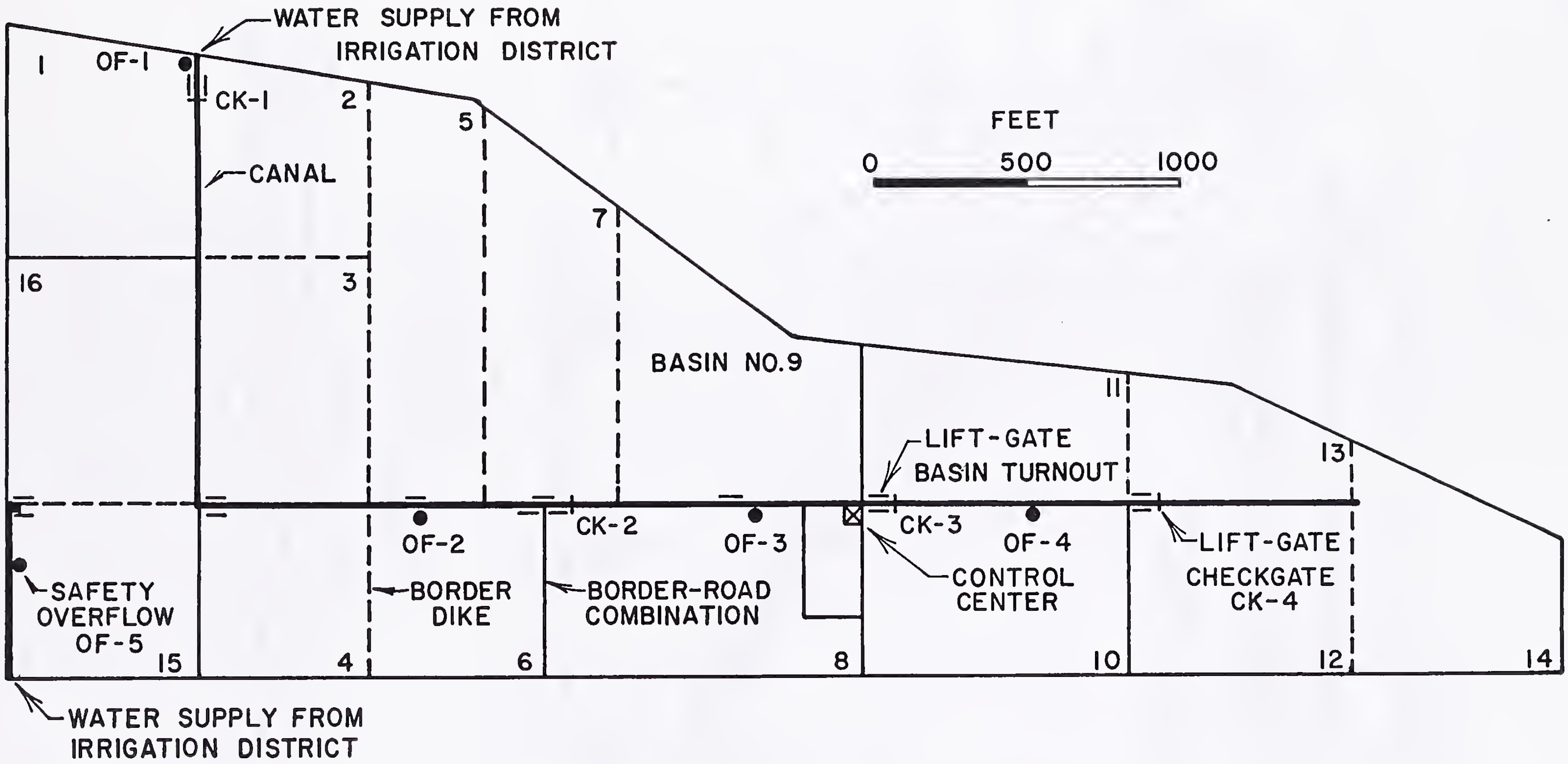

Figure 2. Field layout for 169 acre mechanized level-basin system on Hoffman Farm (HE #4) located in the Wellton-Mohawk Irrigation and Drainage District. The system was installed in January 1986.

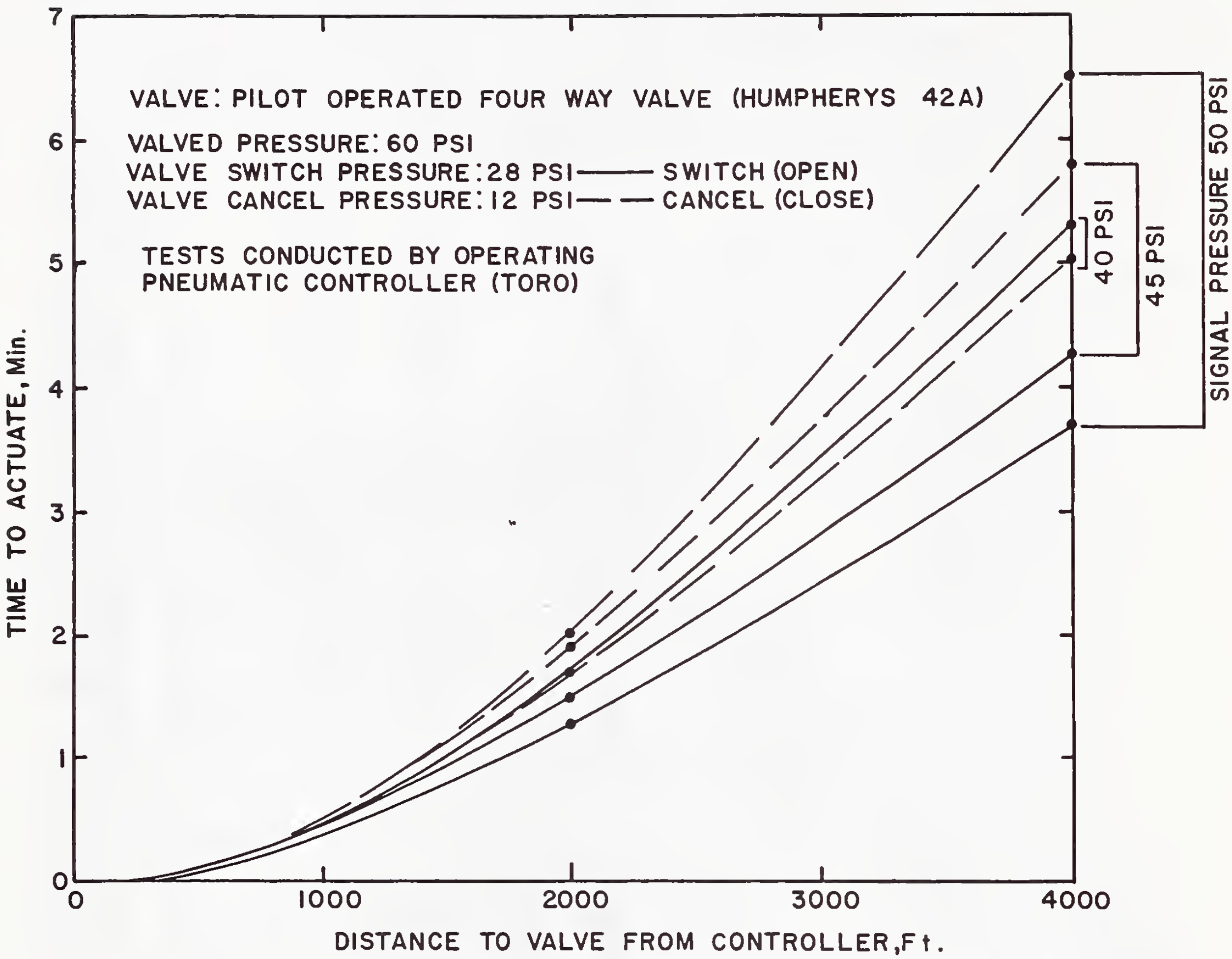

Figure 3. Relation between distance and signal pressure on the time required for an air-pilot operated four-way valve to actuate (pressurize-gate open) and deactivate (depressurize-gate close). The signal line tubes were 3/16-in. ID polyethylene.

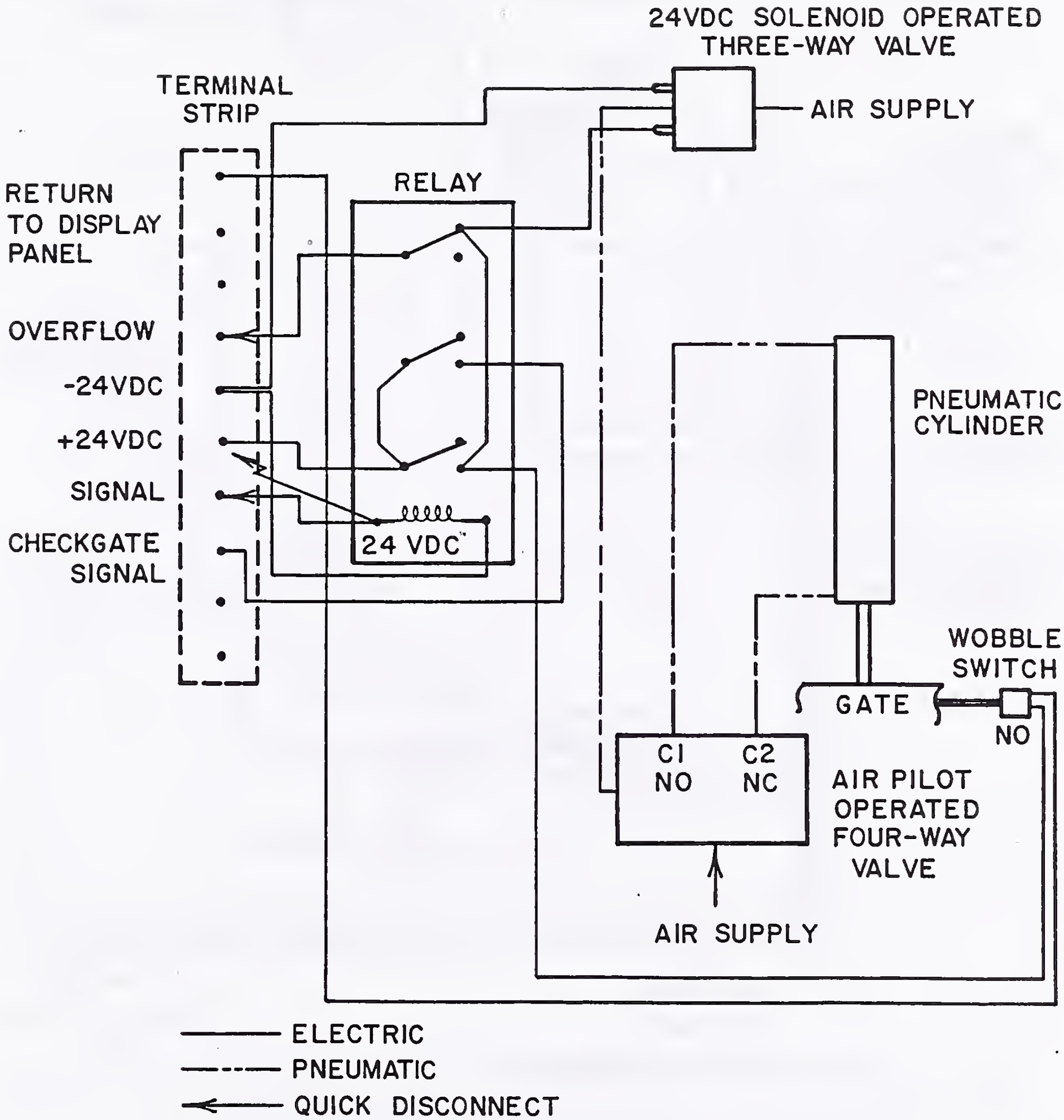

Figure 4. Diagram of electrical and pneumatic layout at a basin gate turnout on the Hoffman mechanized irrigation systems (HE #3 and HE #4). Key parts include a 24 VDC relay, a 24 VDC solenoid operated three-way valve, and an air-pilot operated four-way valve. The arrangement shown provides a normally closed gate (no signal, gate closed). The wobble switch is actuated when the gate opens and comes in contact with the switch, sending a 24 VDC signal back to the control center to power an indicator light and clock. Override, interrupt, and overflow selection are accommodated by electrical quick disconnects. NC and NO indicates normally closed and normally open.

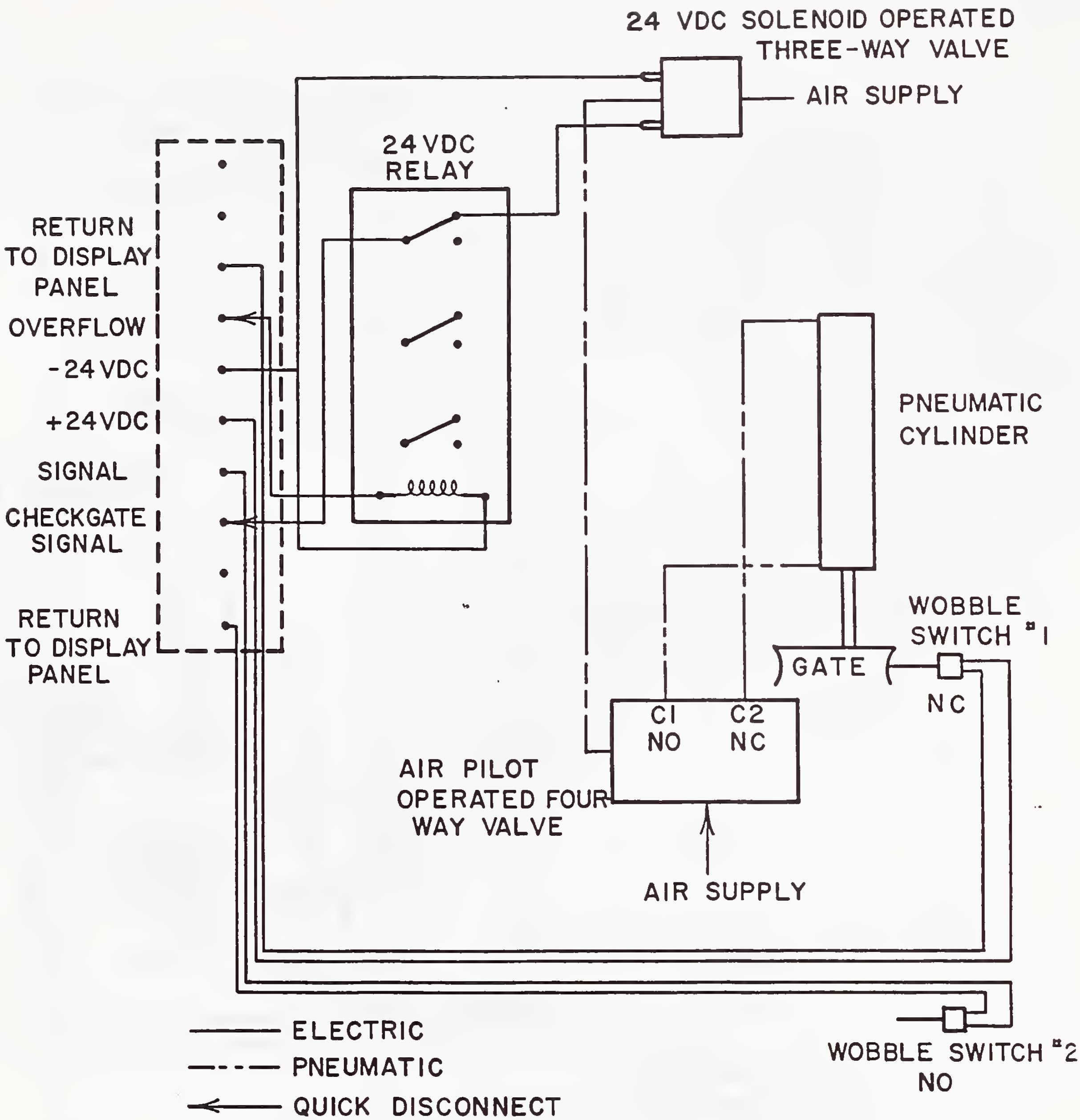

Figure 5. Diagram of electrical and pneumatic layout at a checkgate on the Hoffman mechanized irrigation systems (HE #3 and HE #4). The arrangement shown provides a normally open gate (no signal, gate open). Wobble switch #1 is used on all check gates to indicate when the gate has closed. If the checkgate also lets water out to a basin (Checks 4 of HE #3 and HE #4, Figure 1 and 2, respectively) wobble switch #2 is added to indicate when that gate is open and irrigating (power to wobble switch from controller signal). All wobble switches are mounted to the gate enclosure and are actuated when the gate is open.

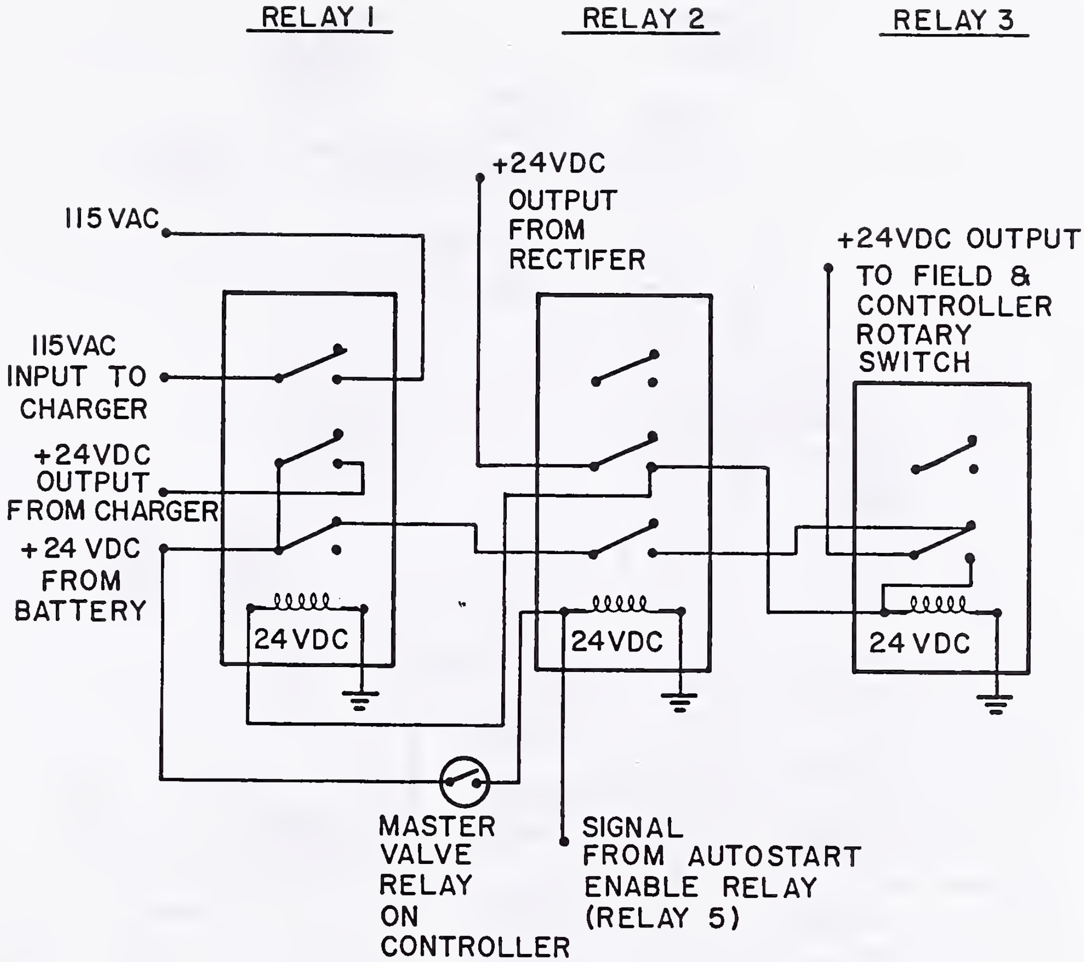

Figure 6. Relay layout used to provide 24 VDC battery backup to the system in case of AC power failure (or interrupted 24 VDC rectified output). Relay 1; activated when irrigating (+ 24 VDC rectified output present); turns on the battery charger, completes the 24 VDC circuit from the charger to the battery, and interrupts the 24 VDC from the battery to relay 2. Relay 2, activated when irrigating (+ 24 VDC from battery through master valve on controller), completes the 24 VDC circuit from the rectifier to relay 3 and from the battery. Relay 3, activated when irrigating (similar to relay 1), switches either 24 VDC from the rectifier to the field and controller rotary switch (if AC power available) or 24 VDC from battery (battery backup if AC power lost).

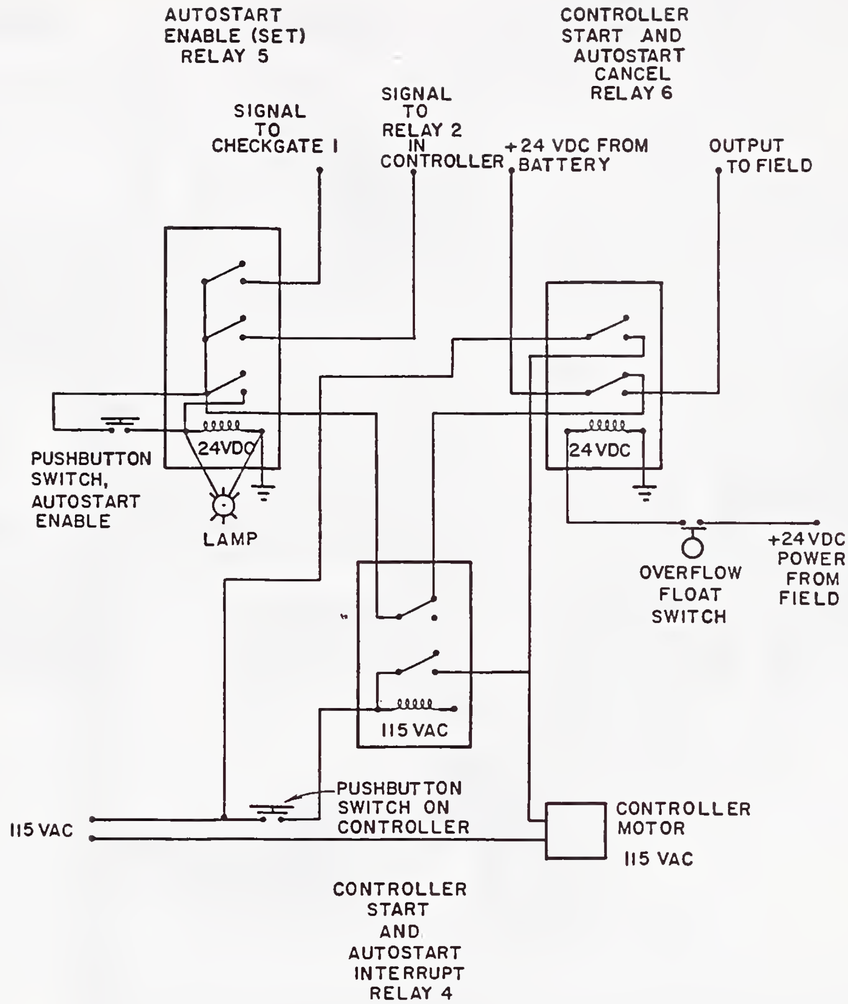

Figure 7. Layout of relays used to remotely start the controller when an overflow (float switch activated) is sensed. System shown is before the remote start was set. To set the system for remote start the operator momentarily closes the push button switch to the left of relay 5, which latches relay 5 and provides a 24 VDC signal to check gate 1 for both systems in Figures 1 or 2 (checkgate closes) and a signal to relay 2 of Figure 6 which initially provides 24 VDC power to the field (daisychained wire). Relay 6 actuates when the float switch closes (canal nearly full of water) which interrupts the power to relay 5 (disables relay 5), continues to provide power to the field until the controller starts, and completes a circuit to start the controller motor and advance the controller to the first station which then starts the irrigation. Once the irrigation has started the water level drops in the canal, the overflow switch cancels, and relay 6 is deenergized. Relay 4 is included for operator convenience to advance the controller to station 1 by using a push button switch located on the face of the controller.

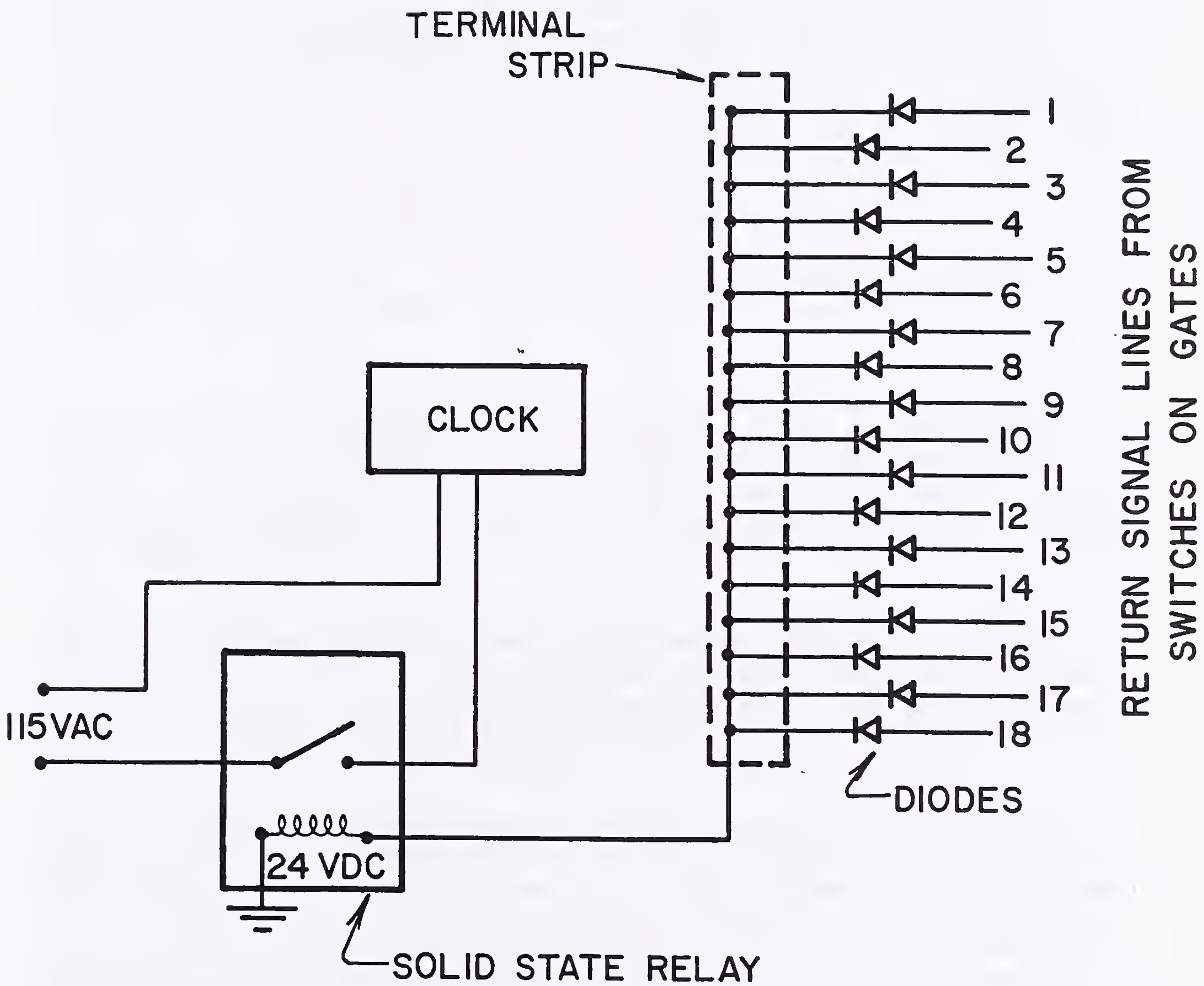

Figure 8. Electrical layout of scheme used to power a 115 VAC clock with a LED display and to interrupt the return signal from different field gates to allow the clock to be reset. The clock is an operator aid in that the time displayed is the lapsed time since the basin gate opened. The diodes are needed to block any feedback to gates not open.

TITLE: DCPTA EFFECT ON GUAYULE RUBBER AND RESIN SYNTHESIS

NRP: 20740 CRIS WORK UNIT: 5542-20740-012

INTRODUCTION

Guayule (Parthenium argentatum Gray), a xerophytic rubber producing shrub indigenous to the Chihuahuan Desert of north-central Mexico and the adjacent Big Bend area of southwestern Texas, has the potential to become a domestic source of natural rubber with quality comparable to the tropically-adapted Hevea brasiliensis (Ray, 1983). Guayule is a highly-branched, symmetrically-shaped perennial shrub of the Compositae Family (Lloyd, 1911). In its native habitat, guayule grows to a maximum height of about 1 m at elevations between 610 and 1830 m on well-drained calcareous soils receiving 25 to 30 cm of rainfall annually (Ray, 1983). In addition to high quality rubber, the guayule plant also produces resins with potential commercial applications as coatings for water resistance and as peptizers (prooxidants) used in rubber processing (Belmares et al., 1980). The bagasse may be used as pulp for paper, as a feedstock, and as a fuel to power the rubber processing plants (Ray, 1983).

At the present time, however, guayule rubber yields are too low to attract commercial production. It is estimated that guayule rubber yields must double before production will be economically feasible at current rubber prices (Wright et al., 1984). This situation may change, however, with changes in the price and availability of sources of Hevea and synthetic rubber.

Guayule breeding efforts are currently underway to increase rubber yields, but it may be five or more years before significant progress is realized (Rubis, 1984). The anticipated progress through breeding may be delayed even further by guayule's complex genetic and reproductive system. Guayule plants have been found with several ploidy levels and may produce seed either by amphimixis or apomixis (Ray, 1983).

Another means of increasing guayule rubber yields may be through the application of plant bioregulators. Studies by Hayman et al. (1974), Hayman and Yokoyama (1976) and Hsu et al. (1974) demonstrated the chemical bioinduction of tetraterpenoids in carotenogenic tissue. Yokoyama et al. (1977) concluded that these bioregulators result in increased synthesis of enzymes in the tetraterpenoid pathway through a process of gene derepression. These studies led to the hypothesis that application of plant bioregulators may increase cis-polyisoprenoid synthesis in guayule.

The compound 2-(3,4-dichlorophenoxy)triethylamine (DCPTA), in particular, has shown promise as a bioregulator for increasing polyisoprenoid rubber production in guayule. The initial studies by Yokoyama et al. (1977)

resulted in 2.7- to 4.3-fold increases in percent rubber of four-month-old greenhouse-grown and eight-month-old field-grown guayule, respectively. The plants in these studies were treated with 5000 ppm DCPTA and sampled three weeks after treatment. While the percentage increase in rubber due to DCPTA treatment appeared to be substantial, the average rubber content of the plants increased from only 1.25 to 3.47 % in the greenhouse and from 0.91 to 3.03% in the field. Rubber percentages of mature guayule plants may be as high as 20% or more (Hammond and Polhamus, 1965).

Benedict et al. (1983) reported a two-fold increase in percent rubber of DCPTA-treated greenhouse-grown guayule. Ten-week-old plants were treated with 5000 ppm of DCPTA at a rate of 5 ml per plant. DCPTA treatment also resulted in a 1.5- to 3.0-fold increase in the activity of the enzymes mevalonic acid kinase, isopentenyl pyrophosphate isomerase, and rubber transferase, all of which are involved in the synthesis of cis-polyisoprene. DCPTA had no effect on plant dry weight.

Further research by Hayman et al. (1983) demonstrated that lower concentrations of DCPTA (125 and 500 ppm) resulted in higher rubber yields. A 91% increase in rubber yield per plant was reported. There was no significant increase in percent rubber of the samples, however. The higher rubber yields were, therefore, due to a DCPTA-induced increase in plant biomass, not percent rubber.

More recent studies by Bucks et al. (1984) showed no significant effects of DCPTA applied to field-grown guayule. Plants in Yuma, Arizona, were treated with 100 ppm DCPTA eight times during 1982 and 1983. The low concentrations of DCPTA were unsuccessful in promoting rubber yields, either by way of increasing percent rubber or plant biomass.

These reports on the effects of DCPTA on guayule rubber yield appear to be contradictory, but a lack of consistent and repeatable results from the bioregulator studies are not unusual. Bhalla (1981) has described the "consistently inconsistent" results obtained through experimentation with the plant growth regulator triacontanol. Another growth regulator, mepiquat chloride, has also produced inconsistent results when applied to cotton (Briggs, 1981), and the effects have been highly sensitive to environmental conditions.

Guayule leaves are covered with a very hard, high molecular weight wax (C 48 to C 54) (Palu and Garrot, 1983 and Ray, 1983). The thickness of the leaf wax is influenced by environment and plant age, with older plants and plants subjected to drought having the thicker layer of wax on their leaves (Lloyd, 1911). Differences in environmental conditions and subsequent differences in cuticle thickness preceding application of bioregulators may restrict the entry of the bioregulators into the leaves, and may account for the differences reported for DCPTA effects.

The results of DCPTA applications to guayule, while inconsistent, indicate a potential for its use in improving guayule rubber yield. No

studies have yet been reported, however, which address the questions of application rates, application timing, or number of applications for optimum rubber yields. The objective of these studies was to determine appropriate concentrations of DCPTA for application to guayule seedlings growing in the greenhouse and transplants growing in the field.

MATERIALS AND METHODS

Greenhouse Study -- Several hundred guayule seedlings (cv. N565 II) were grown from seeds planted in medium-grained vermiculite in the greenhouse between 7 and 15 January 1985. At approximately one month of age 195 seedlings of uniform size were individually transplanted into 6.6 l pots containing a peat-vermiculite mix (3:1 v:v). The plants were fertilized with a complete water soluble fertilizer (Peters Hydro-Sol 5-11-26 with micronutrients) twice-weekly throughout the experiment.

Plants were treated at two months of age with solutions of 0, 375, 750, 1500, 3000 or 6000 ppm DCPTA in combination with 0.0 or 1.0% DMSO. The treatment solutions all included 0.01% Ortho X-77 spreader. A control of distilled water was also included in the experiment, but produced the same results as the 0 ppm DCPTA-0.0% DMSO-0.01% X-77 treatment so was not included in the data analysis. Three subsamples of each treatment were completely randomized in each of 5 blocks, for a total of 15 plants per treatment. Subsample means were used in all subsequent analyses.

Treatment solutions were applied with small hand-held plastic sprayers. The plants were sprayed until the abaxial side of all leaves were completely wetted, which resulted in a volume of approximately 12 ml being applied per plant.

The appearance of each plant was rated on a 1 to 10 scale on days 12, 18, 25, and 32 after treatment. A rating of 1 represented a completely dead plant, and 10 represented a completely healthy plant. Numbers in between the two extremes corresponded to varying degrees of tissue desiccation and chlorosis.

Entire plants were harvested on April 16, 1985 and the fresh weight of the above and below ground plant material recorded. Dry weights were measured after the samples were allowed to dry at ambient temperature in a shaded lathhouse for approximately three weeks. The samples were then ground through a 2 mm screen prior to determination of rubber and resin content by a gravimetric procedure described by Black et al. (1983). Dry weight, percent moisture, percent rubber, percent resin of the above and below ground samples, and total rubber and resin yield per plant were analyzed using an analysis of variance.

Field Study -- A total of 720 two-month-old guayule seedlings (cv N565 II) were transplanted from the greenhouse into field plots at the U. S. Water Conservation Laboratory. One-half of the plots in each of the two blocks were planted on October 12, 1984, and the rest of the plots were planted on March 7, 1985. Prior to planting the plots were rotatilled

and fertilized with 50 lbs acre^{-1} N as ammonium phosphate. The soil was an Avondale loam (Antropic Torrifluvent, fine loamy, mixed, calcareous, hyperthermic).

An experimental unit consisted of 3 rows of 12 plants, with 300 mm row spacing and 150 mm between plants within a row. The treatments consisted of the two planting dates and 5 treatment solutions (a control of distilled water and 100, 400, 1600, and 6400 ppm DCPTA). Each treatment solution contained 0.01% Ortho X-77 as a wetting agent. The 2 x 5 factorial treatments were completely randomized in each of two blocks. Bioregulator application was on May 6, 1985, between 0830 and 0900 hr MST.

Each block contained 2 260 cm deep access tubes for measurement of volumetric soil water content with a neutron moisture probe. Soil moisture content was measured weekly for use in irrigation scheduling. The plots were flood irrigated three times between October 1984 and April 1985. Subsequent irrigations were made with a surface drip irrigation system at approximately two week intervals until the end of the experiment.

Five plants in each plot were harvested twice for gravimetric analysis of rubber and resin content as well as plant height, fresh weight, and dry weight measurements. Harvest dates occurred at 60 and 120 days after treatment (5 July and 3 September). Statistical analyses were performed using the mean values obtained from the five subsamples in each plot at each harvest date.

RESULTS AND DISCUSSION

Greenhouse Studies -- The appearance rating data is summarized in Figure 1. At 12 days after treatment there were very obvious differences among the treatments, with the plants receiving the highest DCPTA levels having the poorest appearance. Between 60 and 70% of the foliage of the plants treated with 6000 ppm DCPTA appeared chlorotic or desiccated. As the experiment progressed, however, the new growth of the DCPTA-treated plants had a normal appearance and the proportion of abnormal foliage decreased. The tissue which was originally chlorotic never recovered, however, and eventually died.

The DMSO had no discernible influence on the appearance of either the treated or control plants. The DMSO-treated plants did, however, release a strong, sweet-smelling odor unlike the odor of plain DMSO. The strong solvent properties of DMSO may have stripped away the cuticle layer of the leaves allowing volatile compounds within the leaves to be released. The emission of volatile hydrocarbons from guayule has been previously reported and the DMSO may have enhanced the hydrocarbon emission (Nakayama et al., 1985).

Results of the analyses of variance for dry weight, percent moisture, rubber and resin, and total rubber and resin per plant are summarized in Table 1. DCPTA had a significant ($P < 0.01$) negative effect on the dry

weight of both the above and below ground plant tissues (Figure 2). The DCPTA not only caused the death of tissue present at the time of application, but it also slowed the growth of new tissue compared to the control plants. The higher the concentration of DCPTA applied, the slower the recovery of the plant and growth of new tissue.

Percent moisture in both the above ground and below ground tissues was significantly affected by DCPTA (Figure 3). Above ground tissue moisture content decreased with increasing DCPTA concentration. At the end of the experiment nearly all of the leaves which died due to the DCPTA treatment were still attached to the plants. These completely desiccated leaves were at least partially responsible for the lowered water content of the top growth of the treated plants.

The DMSO also caused a significant ($P < 0.01$) reduction of percent moisture in the above ground tissue. This result suggests that the DMSO may have damaged or removed the cuticle layer of the leaves causing greater cuticular water loss. Moisture content of below ground samples increased with increasing DCPTA concentration. The reason for this result is not known. The DMSO treatment had no significant effect on percent moisture of the below ground tissues.

Percent rubber in all samples was very low, less than 1.3%, and no statistically significant treatment differences were observed (Figure 4). A low percentage of rubber in young guayule plants is common (Curtis, 1947). The percentage of rubber increases, however, with plant age as the proportion of secondary tissues capable of storing rubber increases. These tissues include the pith, secondary xylem, phloem and cortex, ray parenchyma, and resin canal epithelium (Healy and Mahta, 1985). The plants in this experiment may not have developed a sufficient rubber carrying capacity to allow DCPTA-induced differences in rubber accumulation to be expressed.

Percent resin of below ground tissue was not affected by DCPTA or DMSO, and DMSO had no significant effect on percent resin of the above ground tissue (Figure 5). However, percent resin was significantly reduced ($P < 0.05$) in above ground tissues by treatment with DCPTA. Resins in guayule, like rubber, are found primarily in the secondary tissues of roots and stems. The DCPTA-induced reduction of growth reduced the proportion of secondary tissues, resulting in a lower percentage of resin with increasing concentration of DCPTA.

Resin and rubber yield per plant both decreased significantly with increasing concentration of DCPTA (Figure 6). This was due primarily to the DCPTA-induced reduction in plant dry weight. Rubber per plant was also reduced significantly ($P < 0.01$) by the DMSO. DMSO treatment resulted in lower average dry weight and percent rubber values, although the values were not statistically significant. Since percent rubber was multiplied by dry weight to obtain total rubber per plant, this multiplicative effect resulted in the significantly lower rubber per plant for the DMSO-treated plants.

Field Studies -- A summary of the statistical analyses of percent rubber, percent resin, plant dry weight and plant height data is presented in Table 2. The fall-planted guayule had significantly higher percent rubber, dry weight, and plant height than the spring-planted guayule at both 60 and 120 days after treatment. Resin content was not significantly affected by planting date.

DCPTA had no statistically significant effect on any of the characteristics that were measured. Trends in the data, however, suggest that DCPTA did influence plant growth and rubber and resin content. The lack of statistical corroboration was probably due, in part, to the use of only two treatment replications. Dry weight (Figure 7), for example was consistently lower at the two lowest DCPTA concentrations than the control or the higher DCPTA treatments. This trend, though consistent for both planting dates and both harvest dates, was most apparent for the largest plants. Plant heights followed the same trend (Figure 8). The two lowest concentrations of DCPTA consistently reduced plant height.

The reason for growth reduction induced by DCPTA is not known and has not been reported by other researchers who have studied DCPTA effects on guayule. In fact, other researchers have reported that DCPTA enhanced the growth of guayule (Hayman et al., 1983 and Hayman et al., 1985). One possible explanation lies in the mode of action of DCPTA. Benedict et al. (1983) showed that the activity of enzymes involved in rubber synthesis increase due to DCPTA. The increased rubber synthesis may act as a sink for assimilates in competition with growth functions which depend on those same assimilates, much the same way as many crops shift their resources toward seed production during the reproductive stage of growth. Figures 9 and 10 support this hypothesis. Resin and rubber content were generally higher at the same DCPTA concentrations that reduced plant growth. Again, this trend was much more apparent for the larger plants.

There was a great difference in the visible effects of DCPTA on guayule between the field and greenhouse experiments. The field-grown plants showed very little discoloration or chlorosis as a result of the DCPTA, and what small amount did occur disappeared within a week. None of the tissue was permanently damaged. As a result, their plant growth was not reduced linearly with increasing DCPTA as was the case with the greenhouse-grown plants.

This differential response of greenhouse- and field-grown plants to DCPTA is likely due to the differences in environments. Field-grown plants receiving full sunlight and lower vapor pressure deficits produce a thicker cuticle that resists penetration of foliar applied chemicals, reducing their effective concentration within the plant. Consequently, determining the proper DCPTA concentration for guayule grown in different environmental conditions may be a potential problem. More testing in a wider range of environments is critical before DCPTA can be used reliably in the field.

Another point of interest is the interactive relationship between DCPTA effects on growth and rubber and resin accumulation. The negative nature of this relationship suggests that any gains in rubber and resin accumulation due to DCPTA may be offset by a reduction in plant biomass. Both rubber and resin content per plant of the field-grown plants were essentially unaffected by DCPTA. However, the larger the plants became in this experiment, the greater the DCPTA effects were on percent rubber and resin content. Perhaps DCPTA would have had a more beneficial effect if the plants had been allowed to grow for a longer period after treatment.

Guayule usually accumulates more rubber during late fall and winter when the plant is not in an active vegetative growth stage. The plants in this experiment were harvested during the summer and early fall before the primary rubber accumulation period. The mode of action of DCPTA would indicate that it could possibly have its greatest effect during those periods when rubber accumulation is normally at its peak. This idea deserves further testing.

These preliminary studies on the effect of DCPTA on guayule provided several important results. First of all, they substantiated earlier reports that DCPTA is capable of promoting rubber synthesis. Secondly, they demonstrated that the correct concentration of DCPTA is critical for eliciting a response, and that the correct concentration will vary according to the growth stage and environmental conditions. Lastly, the field study indicated that DCPTA concentrations which promote rubber synthesis also have a negative effect on plant growth. This relationship needs more detailed study to determine whether the reduction in growth offsets the potential benefits of greater rubber and resin accumulation.

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PERSONNEL

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Table 1. Summary of statistical significance from analyses of variance for dry weight, percent moisture, and rubber and resin content of greenhouse grown guayule treated with five levels of DCPTA and two levels of DMSO.

	Source of variation		
	DMSO	DCPTA	DMSO X DCPTA interaction
Dry weight			
Above ground	ns	**	ns
Below ground	ns	**	ns
Percent moisture			
Above ground	**	**	ns
Below ground	ns	**	ns
Percent rubber			
Above ground	ns	ns	ns
Below ground	ns	ns	ns
Percent resin			
Above ground	ns	*	ns
Below ground	ns	ns	ns
Yield per plant			
Rubber	*	**	ns
Resin	ns	**	ns

*, ** Significant at .05 and .01 level, respectively.

Table 2. Summary of statistical significance from analyses of variance for percent rubber, percent resin, plant dry weight, and plant height of spring and fall planted guayule (line N565 II) harvested 60 and 120 days after treatment with 0, 100, 400, 1600, and 6400 ppm DCPTA.

Source of variation	Degrees of freedom	Mean square values: Percent rubber	Percent resin	Plant dry weight	Plant height
		60-day harvest			
Blocks	1	0.254	0.50	0.5	11.6
Treatments	9	0.262	1.23	489.5	95.8*
Plant age (A)	1	1.9977**	1.19	3564.5**	668.2**
ppm DCPTA (D)	4	0.043	2.38	177.9	39.1
A X D	4	0.052	0.09	32.2	9.4
Error	9	0.084	0.68	297.5	22.3
$S\bar{y}$		0.205	0.58	12.20	3.34
		120-day harvest			
Blocks	1	0.018	2.05	1248.2	27.3
Treatments	9	0.120	1.22	195.4	96.8
Plant age (A)	1	0.730**	1.47	12741.2**	670.4**
ppm DCPTA (D)	4	0.037	1.91	546.5	35.3
A X D	4	0.051	0.72	642.0	14.8
Error	9	0.119	2.13	352.0	38.3

*, ** Significant at 0.05 and 0.01 level, respectively.

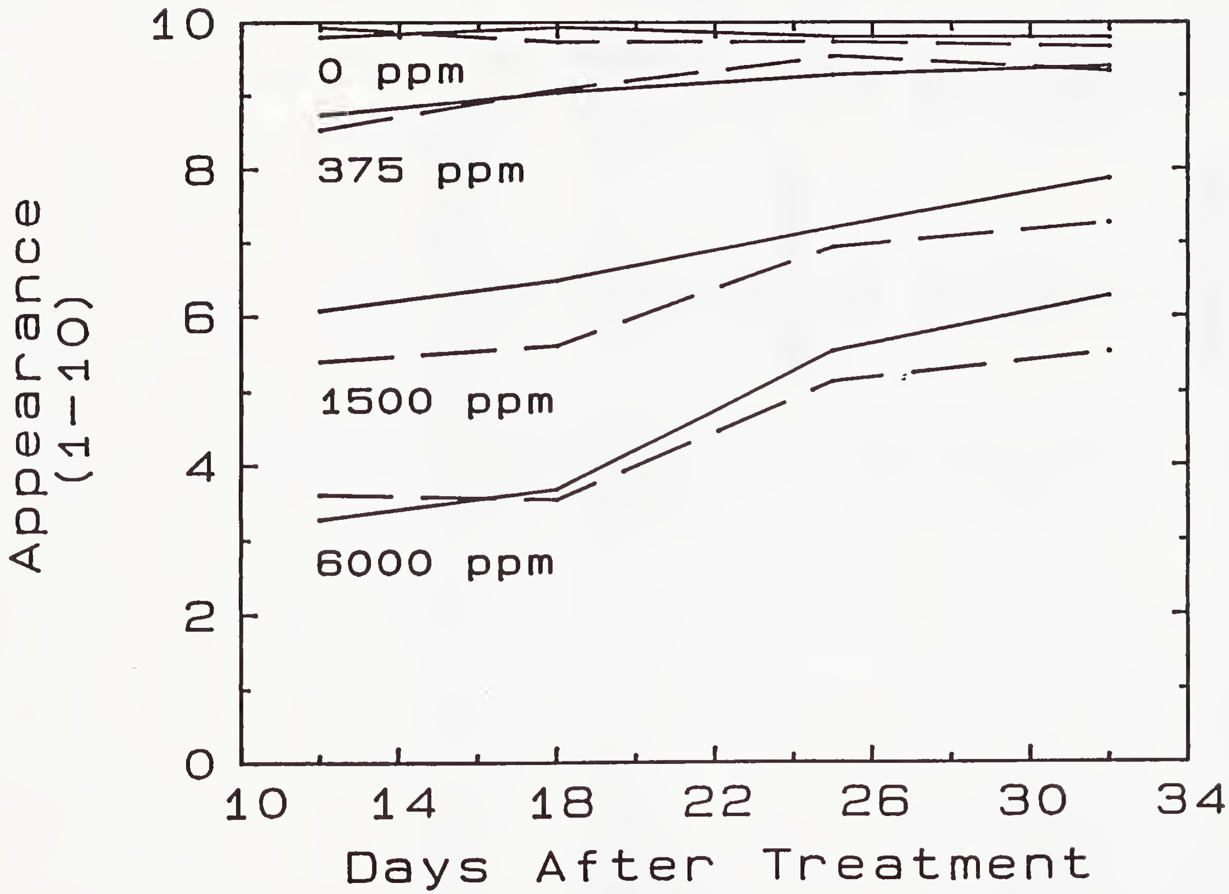


Figure 1. Appearance rating of greenhouse-grown guayule treated with 0, 375, 1500, and 6000 ppm DCPTA and 0 (solid line) or 1% (dashed line) DMSO. Ratings of 0 and 10 represent dead and normal healthy plants, respectively.

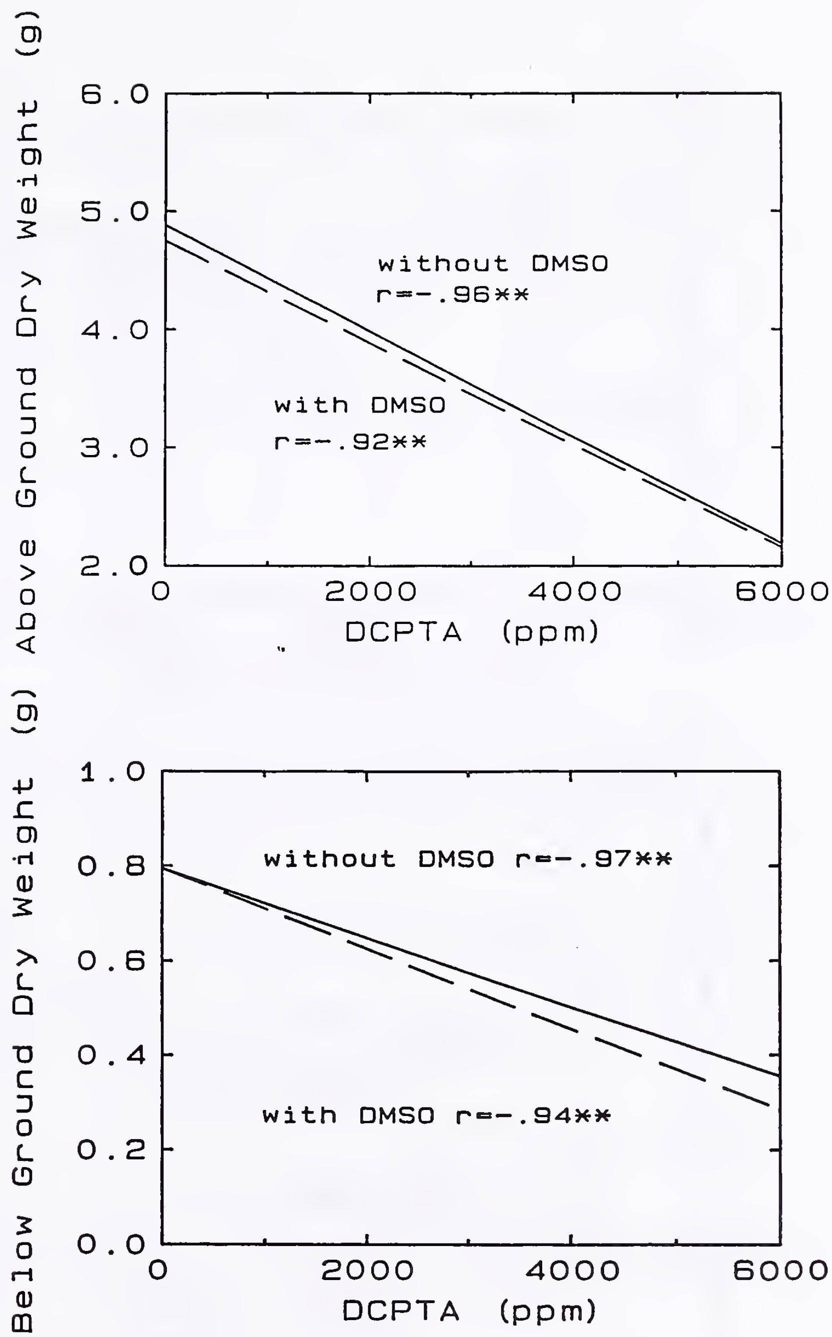


Figure 2. Linear regression of above (top graph) and below (bottom graph) ground dry weight of greenhouse-grown guayule onto DCPTA concentration. Plants were also treated with 0 (solid line) or 1% (dashed line) DMSO.

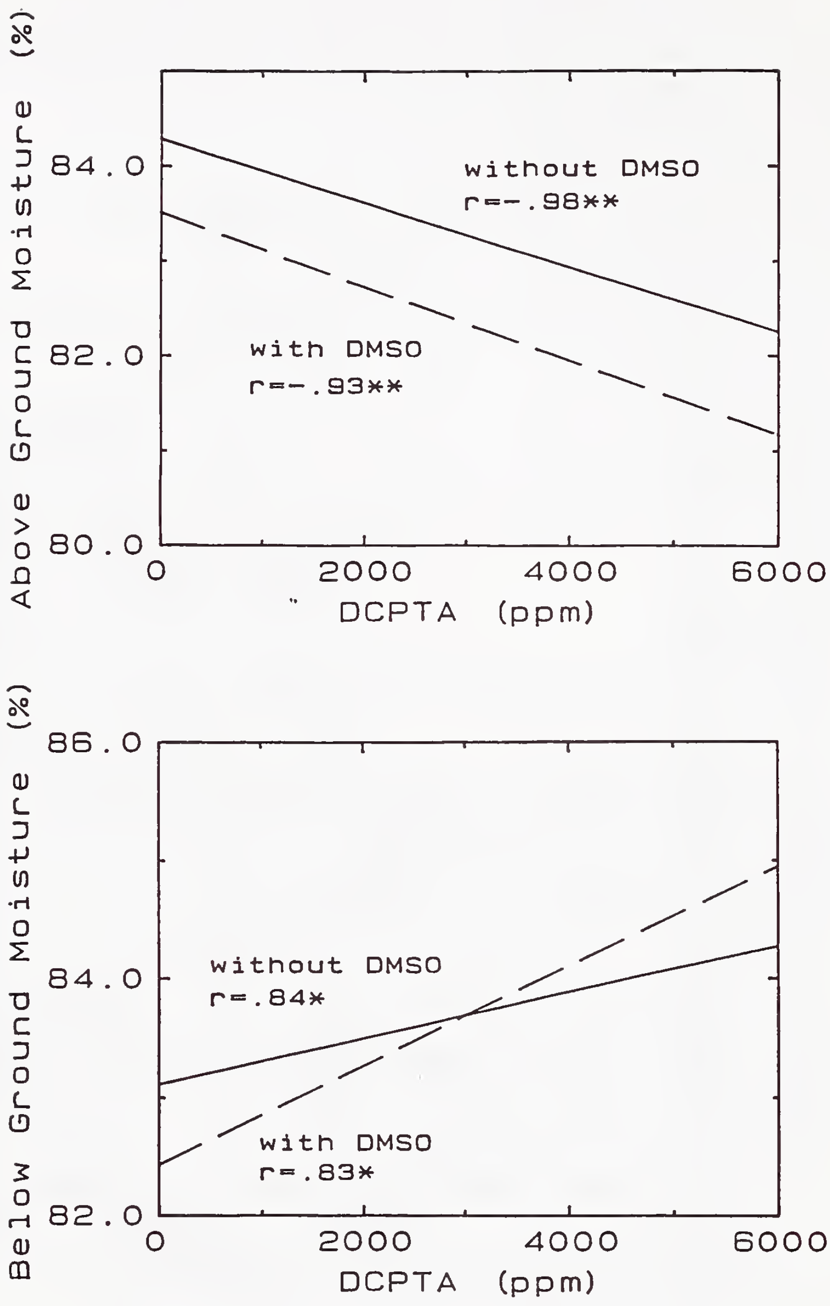


Figure 3. Linear regression of above (top graph) and below (bottom graph) ground percent moisture of greenhouse-grown guayule onto DCPTA concentration. Plants were also treated with 0 (solid line) or 1% (dashed line) DMSO.

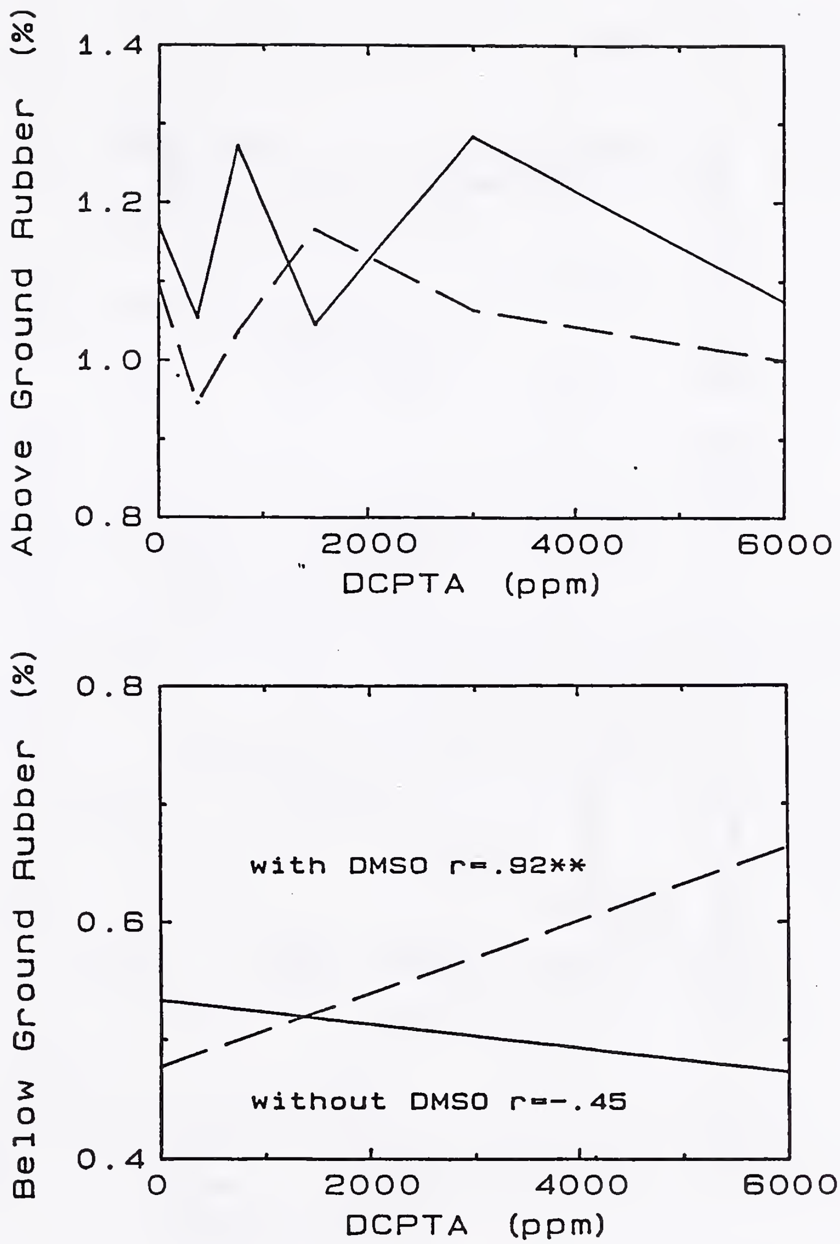
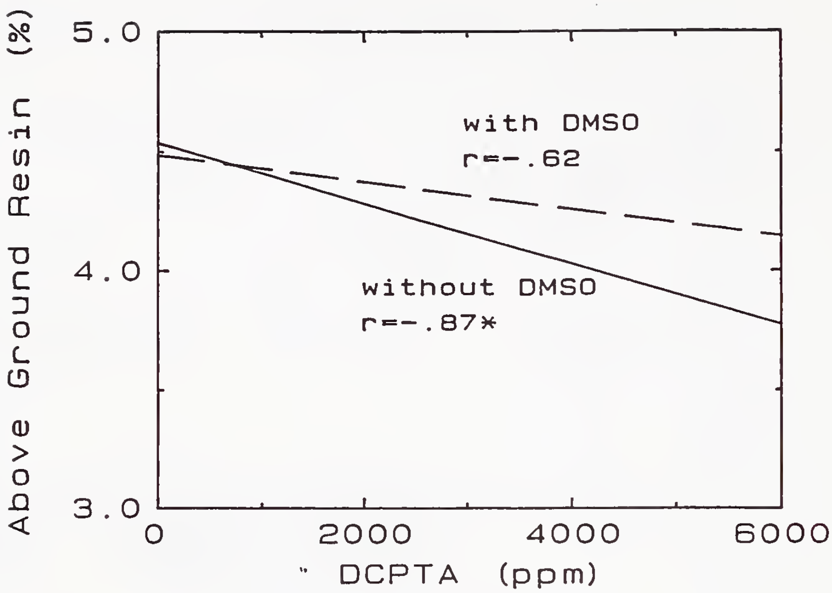


Figure 4. Relationship between above (top graph) and below (bottom graph) ground percent rubber of greenhouse-grown guayule and DCPTA concentration. Plants were also treated with 0 (solid line) or 1% (dashed line) DMSO.



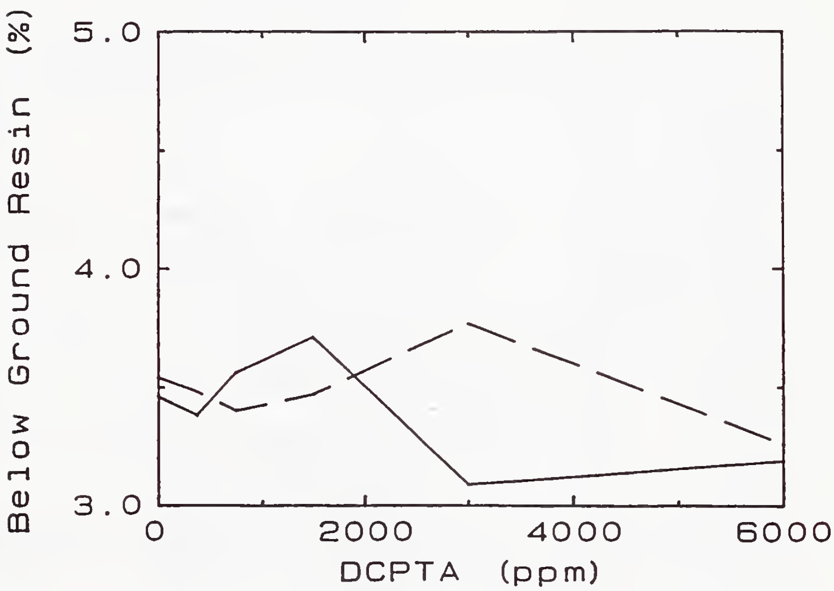


Figure 5. Relationship between above (top graph) and below (bottom graph) ground percent resin of greenhouse-grown guayule and DCPTA concentration. Plants were also treated with 0 (solid line) or 1% (dashed line) DMSO.

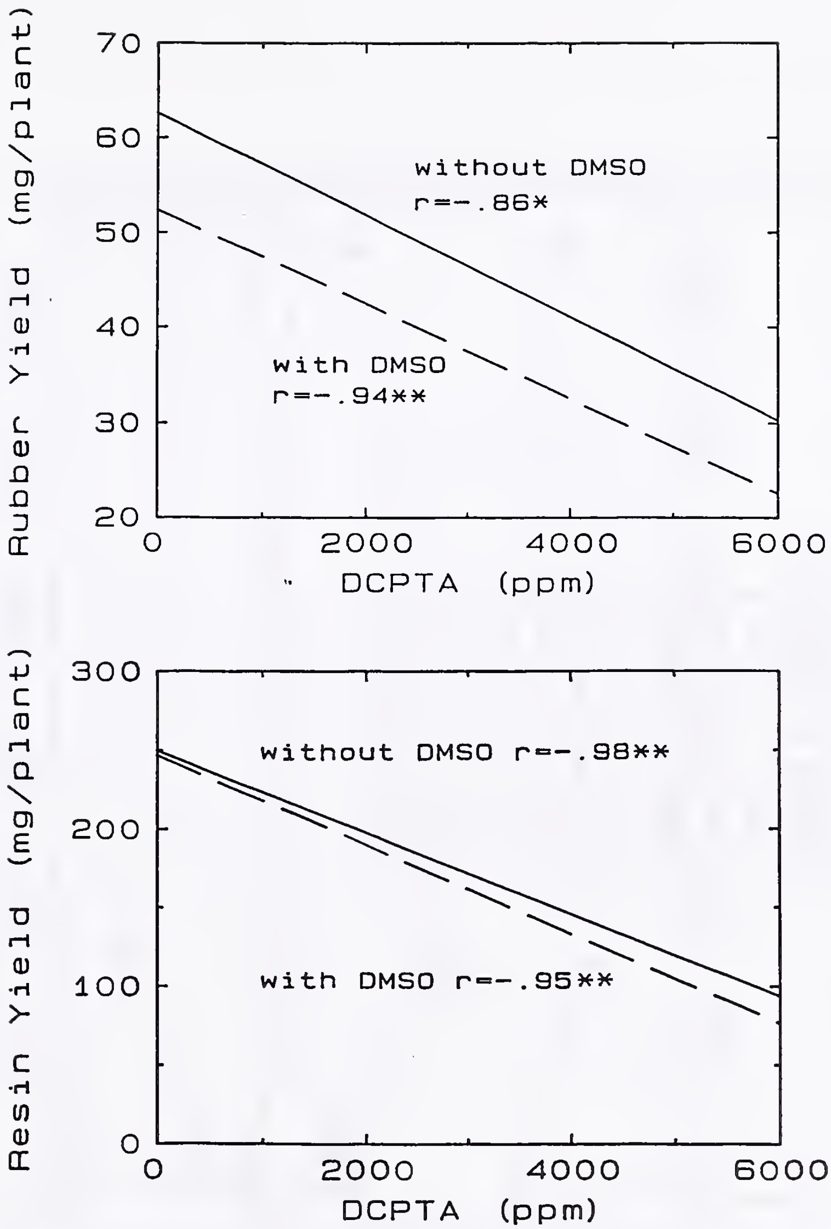


Figure 6. Linear regression of rubber (top graph) and resin (bottom graph) yield per plant of greenhouse-grown guayule onto DCPTA concentration. Plants were also treated with 0 (solid line) or 1% (dashed line) DMSO.

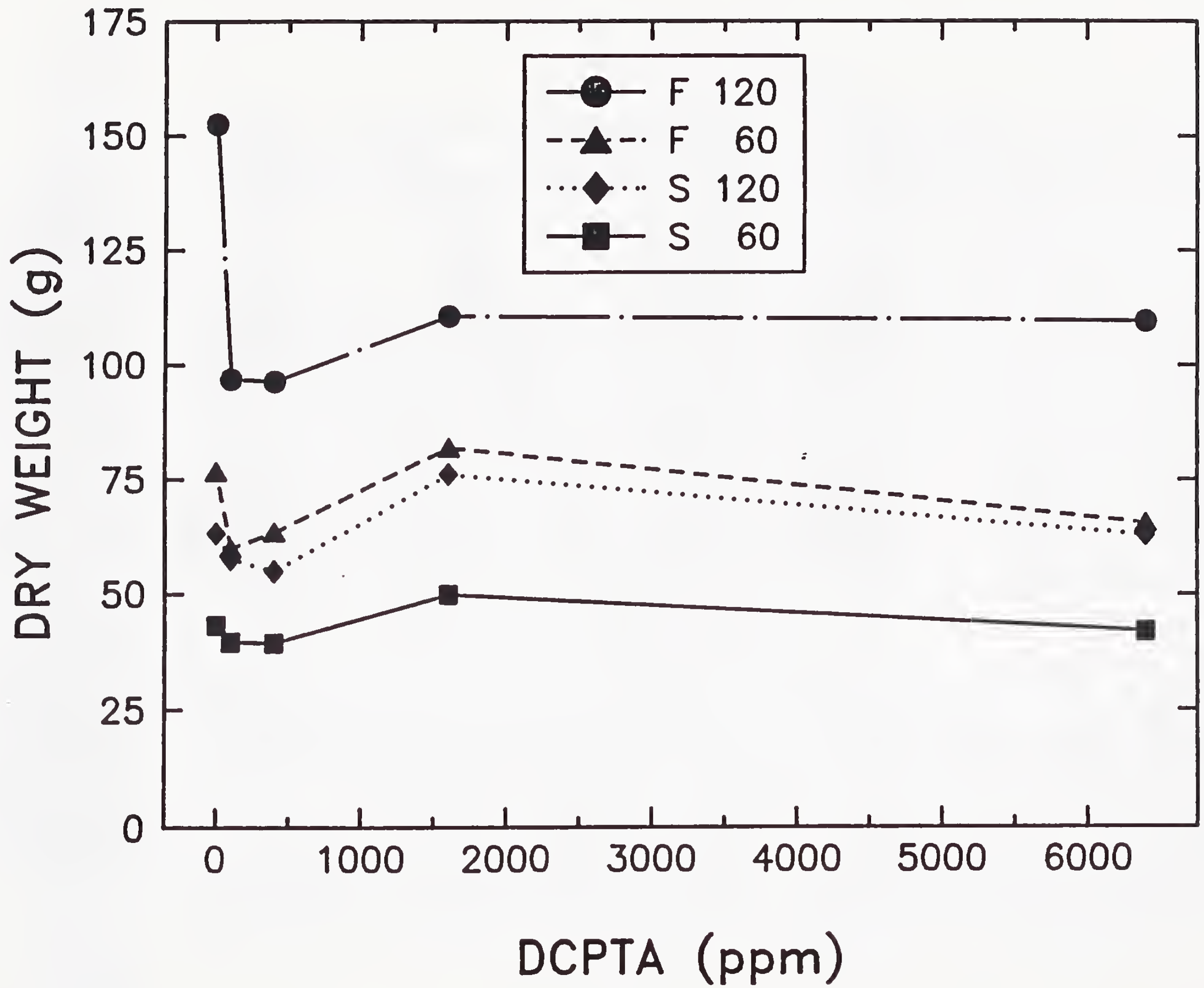


Figure 7. Relationship between dry weight and DCPTA concentration of fall planted (F) and spring planted (S) guayule at 60 and 120 days after DCPTA treatment.

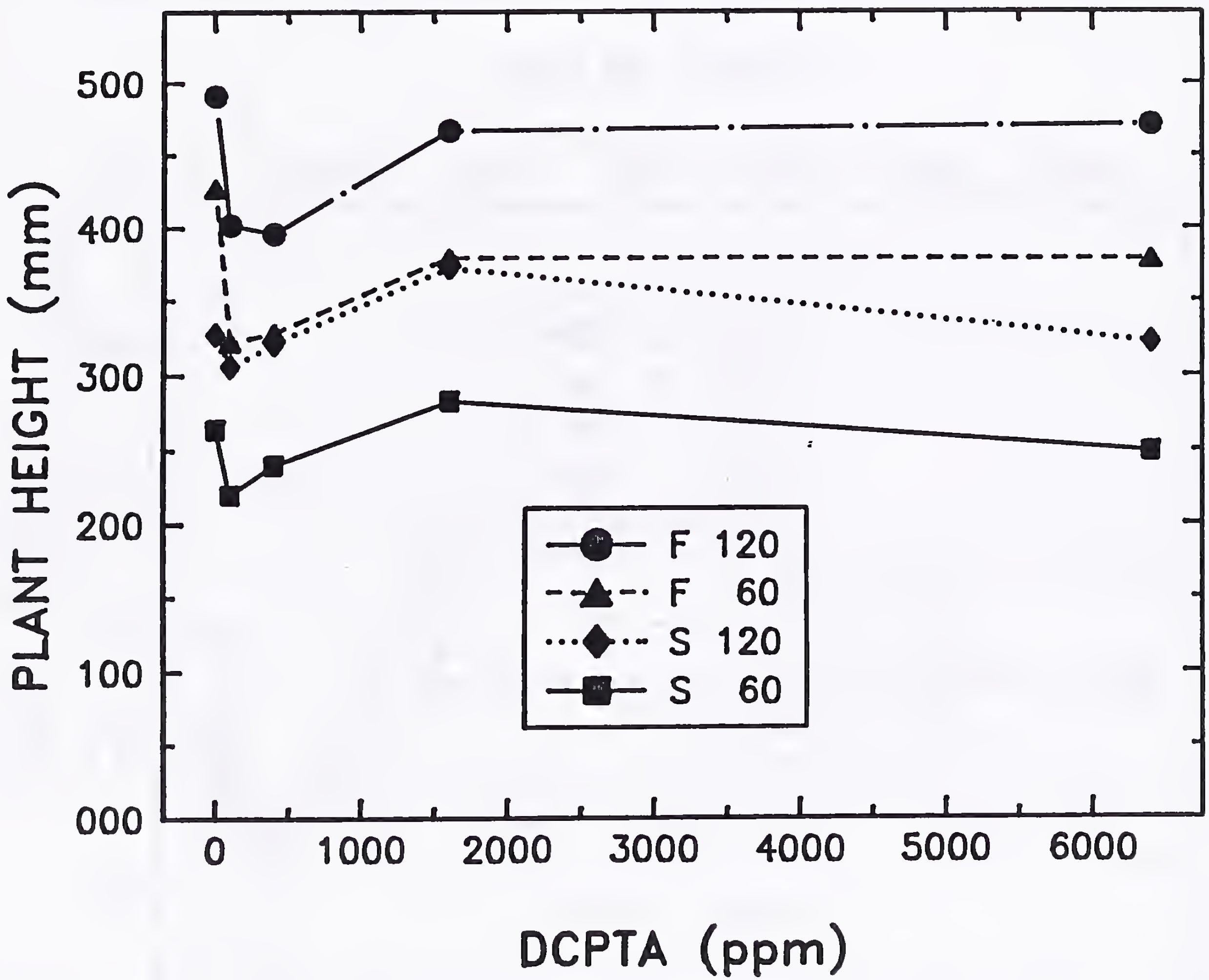


Figure 8. Relationship between plant height and DCPTA concentration of fall planted (F) and spring planted (S) guayule at 60 and 120 days after DCPTA treatment.

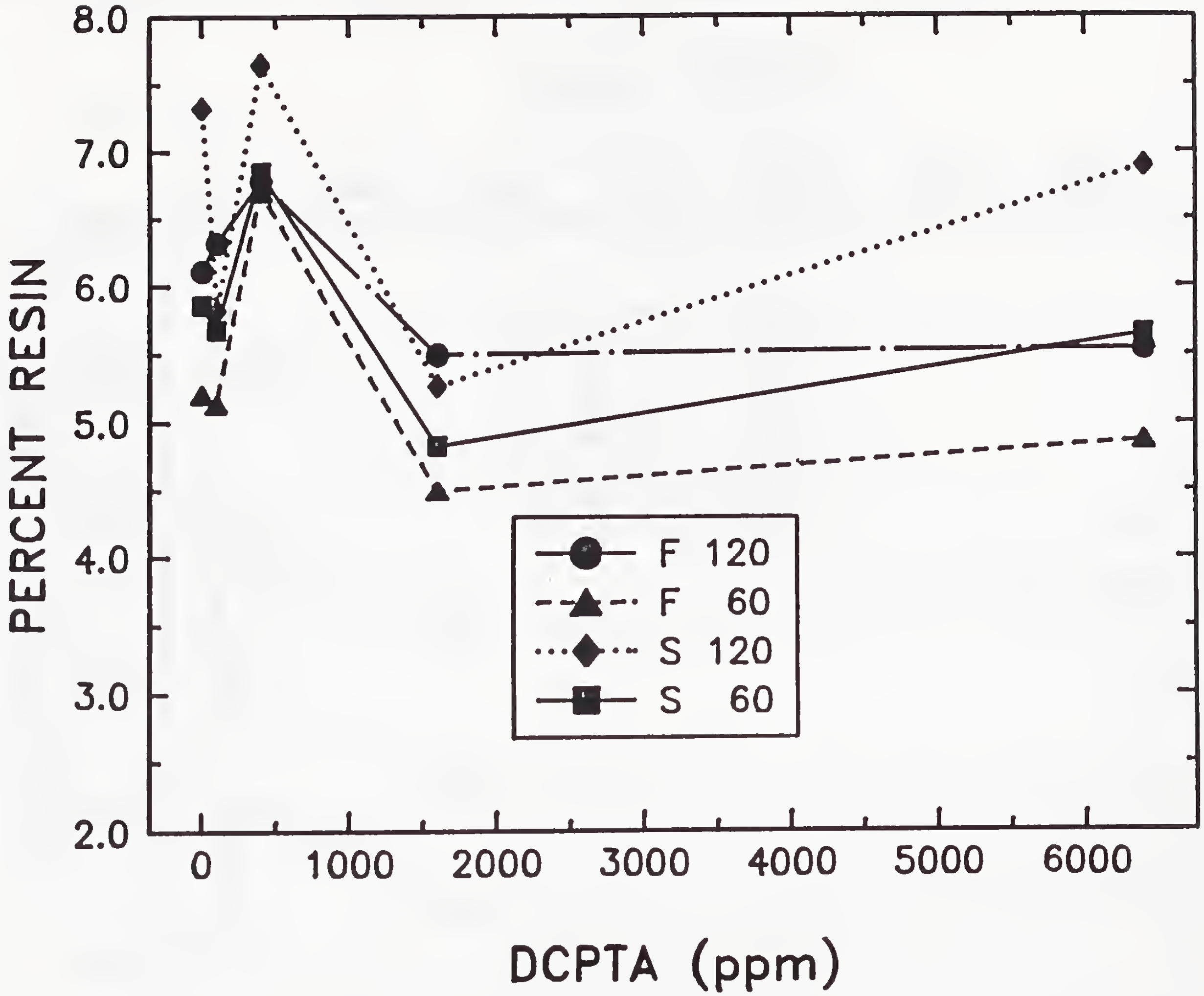


Figure 9. Relationship between percent resin and DCPTA concentration of fall planted (F) and spring planted (S) guayule at 60 and 120 days after DCPTA treatment.

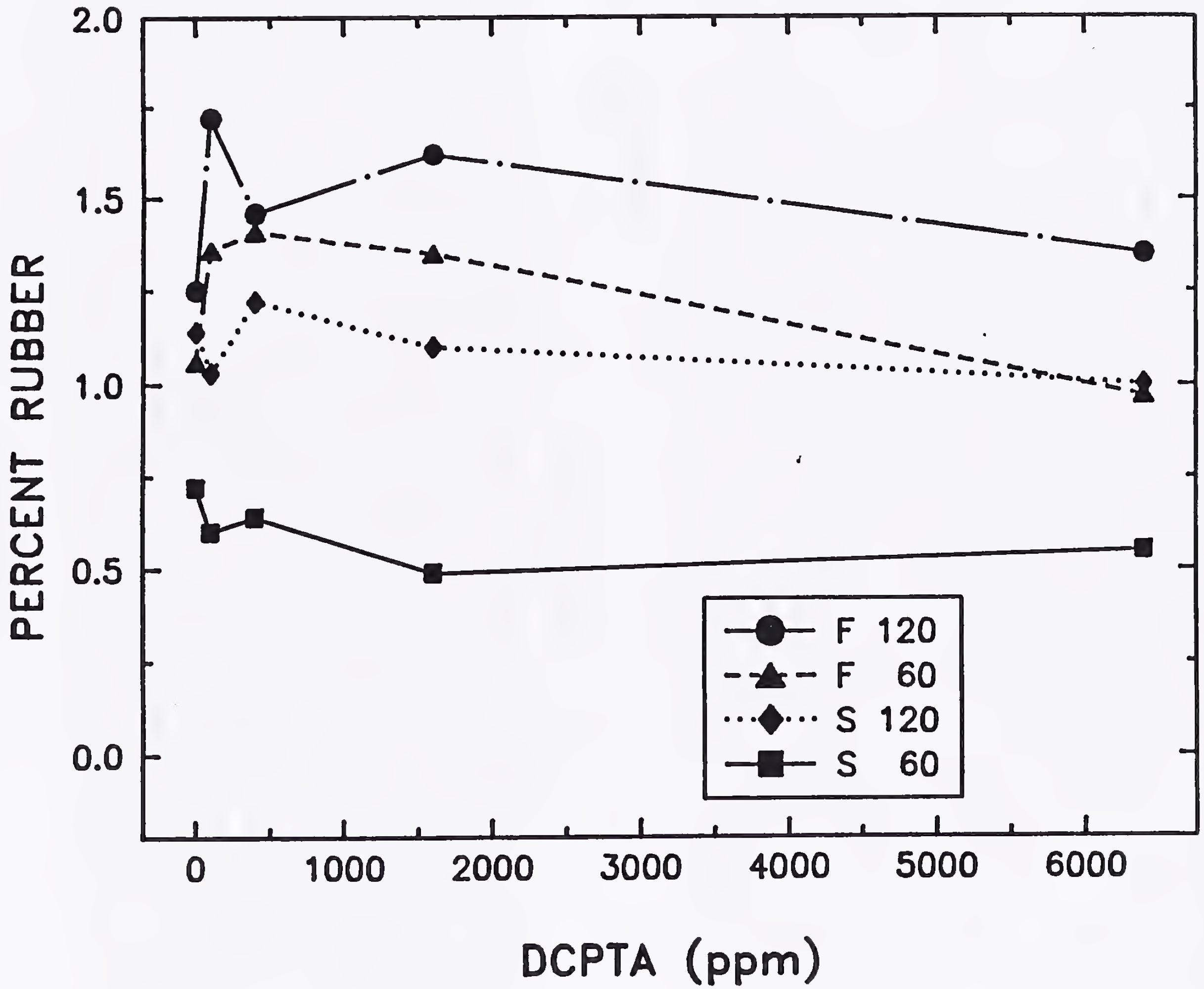


Figure 10. Relationship between percent rubber and DCPTA concentration of fall planted (F) and spring planted (S) guayule at 60 and 120 days after DCPTA treatment.

TITLE: DIRECT SEEDING FOR ECONOMICAL GUAYULE RUBBER PRODUCTION

NRP: 20740 CRIS WORK UNIT: 5542-20740-012

INRODUCTION

Commercial production of guayule (Parthenium argentatum Gray) has been hindered by expensive or inappropriate agronomic practices, particularly the techniques associated with stand establishment. In the past, guayule has been established through transplanting of nursery-grown plants into the field; and more recently, greenhouses have been used for growing the seedlings. The cost of guayule establishment based on greenhouse production and transplanting can be estimated in 1985 to be from $900 to $1200/ha (based on 30,000 plants/ha at $0.03 to $0.04/transplant). The development of direct seeding techniques could possibly reduce this cost to less than $400/ha (based on $300/ha for comparable vegetable seeds plus $100/ha for planting). Unfortunately, earlier field experiences with guayule direct seeding have been marginally successful, suggesting that direct seeding could be feasible only under certain management or environmental conditions. The objective of this study is to establish field procedures for obtaining reliable and economical direct seeding of guayule. Previous field and laboratory tests have shown that germination has been improved by conditioning seeds with polyethylene glycol (PEG), gibberellic acid (GA), and light.

FIELD PROCEDURES

Spring 1985

Twelve rows were planted on April 9 and May 15, 1985, using two planting methods, three seeding rates, and two seed cultivars at Yuma, Arizona, on a sandy soil. All guayule seeds were conditioned using a solution of 25% PEG (MW 8000), 0.2% Thiram fungicide, adjusted to pH 8 with $Ca(OH)_2$, 0.5 mg/ml KNO_3, and 10^{-4} M GA under a continuous light treatment for 3 to 4 days at 25°C (77°F). The planting methods were fluid drilled seeds with a fluid driller and precision planted seeds with a Nibex 300 (plastic-cup feed) planter. The seeding rates were 20 seeds/m (6 seeds/ft), 40 seeds/m (12 seeds/ft), and 80 seeds/m (24 seeds/ft). The two seed cultivars were Salinas mixed bulk (22% maximum germination) and cv. 11591 (64% maximum germination). Three additional rows of Salinas mixed bulk were direct seeded with the precision planter at three depths: soil surface, 2.5 mm (0.1 in), and 5 mm (0.2 in). Irrigation water was applied as an overhead mist using an automated, lateral-move sprinkler system.

Fall 1985

Twelve rows were planted on October 24. 1985, with three levels of phosphate (P_2O_5) and four levels of nitrogen (N) fertilizer in a randomized block design with four replicates. Treble superphosphate was applied and incorporated as a preplant application at 0, 56, and 112 kg/ha (0, 50, 100 lb/ac) of P_2O_5; and liquid ammonium nitrate (NH_4NO_3) was top

dressed at 12, 25, and 37 kg/ha (11, 22, 33 lb/ac) of N with 12, 6, and 4 applications for a total of 148 kg/ha (132 lb/ac) plus zero N starting three weeks after planting. The guayule seeds were cv. 11591 (64% maximum germination) which were conditioned in the same manner described for the Spring 1985 and planted at 40 seeds/m (12 seed/ft) using the fluid drilling planter. In addition, three rows of cv. 11591 seeds were direct seeded using the Nibex 300 precision planter to place seeds at three depths: soil surface, 2.5 mm (0.1 in), and 5 mm (0.2 in).

RESULTS AND DISCUSSION

Spring 1985

Seedling emergence and plant establishment were consistent for the two Spring 1985 plantings, except with the better-quality cv. 11591 seeds. When the later planted (May 15) cv. 11591 seeds were compared to the early planted (April 9) seeds, the plant survival rates declined with time, possibly because of higher soil temperatures and other seed dormancy or management factors. As expected, the better-quality cv. 11591 seeds resulted in higher germination and survival rates than the Salinas mixed bulk. The fluid drilled seeds began to emerge in 4 to 6 days for both planting dates; however, the precision planted seeds emerged over a longer period of 5 to 10 days, possibly because of nonuniformities in seed placement depth. A total of 320 and 526 mm (12.6 and 20.7 in) of irrigation water was applied to the early and late Spring plantings, respectively, during the first 3 months.

After the 3-month establishment period, the field germination rates based on the total number of seeds planted for the fluid drilled seeds averaged 9 to 11% for the early and later plantings, respectively; however, the germination rates for the precision planted seeds averaged 2 to 6% for the two planting dates (Table 1). Field germination rates based on the total number of seeds planted averaged about 3 and 11% (plant survival rates calculated as the field germination divided by the maximum expected laboratory germination were 15 and 17%), respectively, for the bulk and cv. 11591 seeds. Also, the better-quality cv. 11591 seeds appeared to perform better using the fluid drilling method at a planting rate of 40 seeds/m (12 seeds/ft), where the final germination and survival rates averaged 12% and 19%, respectively, for both planting dates. Based on the Spring 1985 plant survival rates, planting at 40 to 60 seeds/m (12 to 18 seeds/ft) with a seed quality of better than 60% laboratory germination should result in 5 to 10 plants/m (1.5 to 3 plants/ft). A planting rate of 40 seeds/m (12 seeds/ft) would require less than 0.5 kg/ha (0.45 lb/ac) of seed to obtain a moderate guayule plant population of 30,000 plants/ha (12,000 plants/ac), which is considerably less seed than used during the Emergence Rubber Projects in the 1940's.

In terms of planting depths, the surface planting with fluid drilling and precision planting method resulted in significantly better emergence and survival than the planting at 5 mm (0.2 in) depth. Very few seeds germinated at the deepest planting depth, as shown in Figure 1. In some

cases, the 2.5 mm (0.1 in) depth was as good as the soil surface planting with the precision planter. Of course, planting depth can vary on the sandy soil, and the sprinkler irrigation method probably buried some seeds that were placed on the soil surface. The advantage of the fluid drilling methods was that the seeds remained closer to the soil surface for a longer period of time. Contrariwise, the fluid drilling method did not space the seeds as uniformly on the soil surface as compared to the precision planting of raw seeds.

Fall 1985

Seedling emergence was good, but plant survival at the first and second true-leaf stage was poor. The primary stand establishment problems were attributed to poor seedling vigor and cool temperatures in early November 1985. Seedling diseases and soil salinity were determined not to be hazards in this case.

SUMMARY AND CONCLUSIONS

Direct seeding of guayule in the field has shown some promise as a means for establishing stands on a sandy soil. To date, best results were obtained when the seeds were properly conditioned with polyethylene glycol, gibberellic acid, and light; planted using fluid drilling or precision planting techniques; and sprinkler irrigated using from 300 to 400 mm of water over a three-month establishment period. The surface-planted, fluid-drilled seeds also showed significantly higher emergence and survival rates than the precision planted seeds placed at deeper depths. Even though satisfactory stands were achieved with the conditioned seeds, poor guayule seedling vigor and not initial seed germination is the main reason for not recommending direct seeding as the preferred method for the establishment of this crop at this time. Direct seeding studies of guayule will continue with a late March 1986 planting at Yuma, Arizona; and in early April at Maricopa, Arizona; and in early April at Maricopa, Arizona. At Yuma, the Fall 1985 experiment will be repeated. At Maricopa, the treatments will include conditioned and unconditioned seeds along with grain intercropped to provide shading for the young seedlings.

PERSONNEL

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Table 1. Final field germination rates after three months for guayule seeds planted on April 9 and May 15, 1985.

Planting Date and Method	Seeding Rate (seeds/m)	Seed Cultivar[1/] Bulk	11591	Average
		(percent germination)[2/]		
April 9				
Precision planted	20	10	11	10.5
	40	4	7	5.5
	80	2	5	3.5
Fluid drilled	20	5	13	9.0
	40	3	18	10.5
	80	5	9	7.0
May 15				
Precision planted	20	0	5	2.5
	40	1	1	1.0
	80	1	2	1.5
Fluid drilled	20	1	22	11.5
	40	3	23	13.0
	80	4	14	9.0
Average		3.3	10.8	

1/ Maximum laboratory germination rate: Bulk = 22%, and cv. 11591 = 64%.

2/ Average of four replicates; final field germination rates are based on the total number of seeds planted at 40 seeds/m (12 seeds/ft).

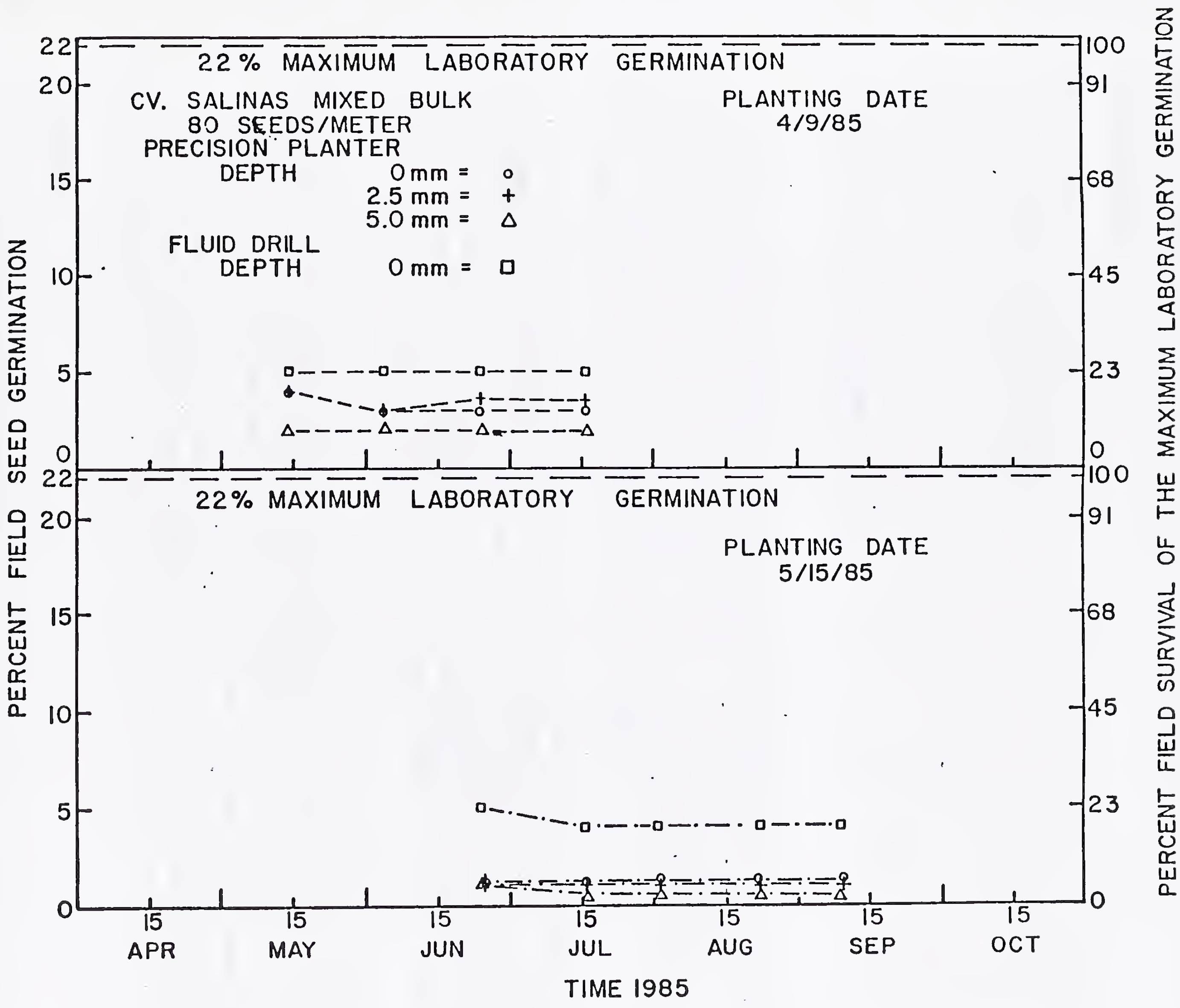

Figure 1. Percent field seed germination and seedling survival rates for three planting depths in the Spring 1985 at Yuma, Arizona.

TITLE: GERMPLASM IMPROVEMENT OF GUAYULE FOR RUBBER PRODUCTION

NRP: 20740 CRIS WORK UNIT: 5422-20740-012

INTRODUCTION:

Both sexual and asexual seed reproduction processes occur in the guayule plant (Parthenium argentatum Gray). Apomixis (asexual) is desirable for maintaining a "pure" line that has proven itself for traits needed for optimal crop production. However, in guayule a high yielding rubber line has yet to be attained. The guayule plant produces both sexual and apomictic seeds at the same time in varying proportions. In germplasm improvement, we must have sexual reproduction to make the necessary crosses to introduce the desirable traits into the progeny in terms of rubber synthesis, disease resistance, salt and water stress tolerance, high or low seed production, etc.

The primary objective for the study is to determine the extent of inheritance of apomixis in guayule occurring in natural stands and new crosses. Laboratory crossing between diploid sexual females with polyhaploid apomictic males could lead to sexual instead of apomictic progenies. Whether the apomictic characteristic can be re-established back into a line following hybridization is not known, but examination of the segregated generation could be used to determine this.

In the natural environment, factors such as water, salt or temperature stresses, and photoperiod could affect the extent of apomixis. Since apomixis in guayule is facultative rather than obligatory, seed purity may be influenced by environment. Thus, another objective of this study is to determine the environmental factors affecting the apomictic process. Such information can be used by plant breeders and particularly so for growers in their seed production work.

Seedling vigor is a problem in plant establishment by direct seeding in the field. Even though guayule is apomictic and embryo formation and development is asexual, endosperm development, which supplies nutrients and energy to the germinating seed, only takes place as a result of pollination. It is not known if other pollen sources could supply this stimulant for endosperm development. The use of foreign pollen sources from different guayule lines, different species of the guayule genus, and different genera of the guayule (Compositae) family could provide this information.

PROCEDURE

In the apomixis inheritance studies, sexual diploids (2n=36) of P. argentatum and asexual apomictic polyhaploids (2n=36) of P. argentatum plants will be crossed using standard crossing procedures. Crosses and seed collection will be made daily while plants are in the reproductive cycle. Cytological evaluation of the parents and offsprings will be made to determine the ploidy levels. Crosses of P. argentatum diploids x P. stromonium, a sexual diploid with conspicuous morphological

features, will be made to determine the mode of reproduction occurring in the F_1 generation. Test crosses of the F_1 to the recessive parent will be made to determine the number of genes involved in the inheritance of apomixis. Additional test crosses will be made with P. stromonium to determine the reproductive mode of the test cross progeny through such interspecific crosses.

Existing field-grown plants of P. argentatum cv. 593 will be used as the female parent for crossing, with P. stromonium serving as the pollen parent. Plants will be subjected to different water stress levels by controlled irrigation application. Crossing will be made over a one-year growing season at varying temperatures, humidity, and photoperiodic conditions, which will be monitored throughout the crossing period. Mature plants will be grown from seeds of these crosses and classified on the basis of morphological characters to determine the degree of apomixis.

Plants of P. argentatum cv. 576 serve as the female parent to test the effect of pollen source on seedling vigor. Six pollen treatments are (1) no treatment, (2) self-pollination, (3) pollen from the same guayule line, (4) pollen from a different guayule line, (5) pollen from P. stromonium, and (6) pollen from sunflower, Helianthus annuus, L. Plants will be grown both in the greenhouse and field. In the later case, the plots will be isolated within screened chambers and bees will be used for enhancing pollination. Collected seeds will be germinated and the effects of the crosses classified in terms of seedling vigor, morphology, cytological and protein composition. Progeny treatment combinations and resulting seed formation will be used to test for self-pollination, incompatibility, and seedling vigor as affected by hormonal stimulation of endosperm development.

A plot of guayule breeding material, approximately 2 acres in size, was established in 1982 on the Wong Farm near Marana, AZ, by Dr. D. D. Rubis of the University of Arizona prior to his retirement. The planting was examined for genetic variability and selection potential in cooperation with Dr. D. T. Ray of the University of Arizona.

RESULTS AND DISCUSSION

Research on all phases of apomixis inheritance is in progress. To date, sufficient data for analysis have not been obtained. The various plants have been collected and crossing started in both greenhouse and field. Field plots are being set up for pollination studies.

On October 29-30, 1985, the guayule breeding material on the Wong Farm near Marana was evaluated. Considerable variability was observed both within and between plots for plant vigor and growth habit, plant height and spread, number of branches, biomass production, flowering, foliage color, leaf size and shape, and disease reaction. Plants within 234 plots were judged to be uniform and most likely the progeny of apomictic selections. Cuttings were taken from 6 plants of each plot for future

maintenance and propagation of the lines. A total of 425 single plant selections were made within 132 plots that exhibited significant plant to plant variability. Selected plants were labeled and cuttings made. Survivial rate of the cuttings from both plots and single plants was relatively low. Additional cuttings will be made in the Spring of 1986 after resumption of vegetative growth.

Plans are made for determination of rubber, resin and biomass production, and rubber quality of all single plant selections and the selected uniform plots. Samples for analysis will be obtained in February 1986 by clipping plant tops at a uniform height. Plants will be allowed to regenerate. Both uniform plots and single plant selections will be evaluated for regeneration capability after at least one year's regrowth, at which time additional samples will be taken for rubber and resin analysis.

SUMMARY AND CONCLUSION

Research has just begun in germplasm improvement of guayule. Considerable breeding material was salvaged from the germplasm field plot established in 1982, which was to be abandoned. Plants are being collected and additional field plots established for determining the mechanism of asexual (apomictic) reproductive seed production, the effect of environment on apomixis, and the effect of pollen source and environment on seed viability. Interpretation will be based on cytological analysis, morphological comparisons, and growth habits of the parents and progenies.

The collection of guayule breeding material at the Wong Farm exhibits an impressive array of genetic variability for plant morphological characters. It is anticipated that genetic variability in rubber and resin production will also be found. This planting will also provide the opportunity to evaluate a wide array of plant types for heritable variation in regeneration potential and yield following clipping. Superior selections will be re-established by vegetative cutting in a nursery planting at the Maricopa Agriculture Center for further breeding and genetic research.

PERSONNEL

D. Dierig, A. E. Thompson, and F. S. Nakayama

TITLE: GUAYULE PRODUCTION RELATED TO WATER AND NUTRIENT REQUIREMENTS IN SANDY SOILS

NRP: 20740 CRIS WORK UNIT: 5542-20740-012

INTRODUCTION

Guayule (Parthenium argentatum Gray) has the potential of becoming a viable crop of both agricultural and industrial importance for rubber and resin production. The successful cultivation of guayule in a non-native, semiarid environment involves the judicious control of both the water and fertilizer applications. However, basic knowledge of the water and fertilizer requirements along with the biotechnological responses has been lacking for mature guayule plants. Early research and demonstration on the drought-tolerant guayule plant had incorrectly assumed that water and fertilizer requirements will always be minimal in the field. The objective of this study was to determine irrigation water and nitrogen requirements for high resin and rubber production from guayule on a marginal agricultural soil. In addition, the potentials for harvesting only the upper portion of the guayule plant by clipping and for applying bioregulators to enhance rubber production were investigated.

FIELD PROCEDURES

The four-year experiment is being conducted on a 0.4 ha (1 ac) field at the University of Arizona, Yuma Mesa Agricultural Center. The soil is a Superstition sand with a soil water intake of about 76 mm/h (3 in/h) and an available soil water capacity of less than 85 mm/m (1 in/ft). Seedlings of three guayule cultivars (593, N565-II, and 11591) were transplanted at a population of 49,500 plants/ha (20,000 plants/ac) in January 1982. The experimental approach is based on a central composite rotatable statistical design with two variables, water and nitrogen. The five water levels vary from 50 to 150% water applied (WA) and nitrogen levels range from 33 to 167% of the recommended nitrogen rate (N). The 100% WA level is based on the evapotranspiration measured for the guayule crop at Mesa, Arizona, on a medium irrigation treatment and varies with plant age. The 100% N level is based on adding 56.4 kg/ha (50 lb/ac) in the early spring and fall of each year. An automated, lateral-move sprinkler irrigation system is used to apply both water and nitrogen. In addition, a portion of each plot is treated with three bioregulator compounds: [2-3,4-dichlorophenoxy)-triethylamine (A); 2-(2,4-dichlorophenoxy)-triethylamine (B); and N-methylbenzylhexylamine (C)] four times per year using concentrations of 100 mg/L. Soil water contents, plant and soil nutrients, and daily meteorological measurements are taken. Periodic harvests of a small number of plants are taken plus a major annual harvest of whole and clipped plants is conducted in January of each year. The results from January 1985 will be discussed in this annual report.

RESULTS AND DISCUSSION

Three years of research has shown that the successful cultivation of guayule requires the judicious control of both the water and nitrogen amounts. Dry weight, rubber concentration, and rubber and resin yield were significantly different for the whole, clipped, and bioregulator plants harvested in 1985 from the agricultural marginal soil of 95% sand. Table 1 shows the non-bioregulator, whole plant harvest data along with the total water and nitrogen applied at the time of harvest on the nine treatments averaged for the three guayule cultivars. Water and nitrogen applications of more than 5280 mm (208 in) and 340 kg/ha (303 lb/ac), respectively, were required to obtain a cumulative rubber and resin yield of greater than 2300 and 2500 kg/ha (2050 and 2230 lb/ac). The optimum 5200 mm (208 in) of irrigation water applied (T_5 treatment) plus 432 mm (17 in) of precipitation was accounted for in a total soil water depletion of about 5420 mm (213 in, estimated evapotranspiration) over the three-year growth period. The rubber yield equation at three years was $RUW = -2809.4 + 1338.0\ WA + 7.08N - 130.72\ WA^2 - 0.0120N^2 + 0.380\ WA \cdot N$ ($R = 0.95$, LOFF = 0.42 NS, $F = 12.4$), where RUW = whole plant rubber yield in kg/ha, WA = total water applied in m (meters), and N = total nitrogen applied in kg/ha. Rubber yield contours for non-bioregulator, whole plants are depicted in Figure 1. Monthly nitrate (NO_3-N) levels for cv. 593 indicated to date that a critical level of about 1500 to 2000 mg/L should be maintained in leaf petioles.

Clipped plants that were cut off at a 100-mm (4 in) height aboveground represented about 51% and 54% of the rubber and resin yield, respectively, for whole plants dug to a 150-mm (6 in) depth. Spray applications of the three bioregulator compounds at low concentrations resulted in clipped rubber and resin yields averaging 925 and 1165 kg/ha (825 and 1040 lb/ac), respectively, whereas the nonbioregulated clipped rubber and resin yields averaged 890 and 1070 kg/ha (795 and 995 lb/ac) for all water and nitrogen treatments. Water-nitrogen production functions were also determined for the clipped plants.

SUMMARY AND CONCLUSIONS

The successful cultivation of guayule in an agriculturally marginal soil of 95% sand was demonstrated in a field study under various water and nitrogen treatment combinations. Water and nitrogen applications of more than 5280 mm and 340 kg/ha, respectively, were required to obtain a cumulative rubber and resin yield of greater than 2300 kg/ha and 2500 kg/ha over a three-year growth period. Spray applications of three bioregulator compounds to guayule at low concentrations, four times per year have not improved resin or rubber yields thus far, suggesting that more work must be done to determine whether higher concentrations or more frequent applications, better penetration of the chemicals, use of different guayule cultivars, or an appropriate age of the plant at treatment can solve this shortcoming. Additional research is needed on optimizing further water and nitrogen use of guayule at an older age,

with newer cultivars and more effective methods of applying bioregulators. The final harvest of four-year-old whole plants will be conducted in late January 1986 on guayule that has not been harvested, previously clipped at two years, and clipped at three years of age.

PERSONNEL

D.A. Bucks, F.S. Nakayama, O.F. French, W.W. Legard, and B.A. Rasnick (U.S. Water Conservation Laboratory); R.L. Roth, B.R. Gardner, and E.A. Lakatos (Yuma Agricultural Center, University of Arizona).

Table 1. Nonbioregulator treated, whole guayule plants harvested on January 23, 1985, from nine treatments averaged for three cultivars at Yuma, Arizona.

Treat-ment	Total[1/] Water Applied	Total[2/] Nitrogen Applied	Dry Weight	Rubber Content	Rubber Yield	Resin Content	Resin Yield
	mm	kg/ha	g/plant	%	kg/ha	%	kg/ha
T_1	2831	341	400 a[3/]	6.6 d	1300 a	7.0 N.S.[4/]	1390 a
T_2	3566	207	504 b	6.5 cd	1621 abc	6.8 N.S.	1696 ab
T_3	3566	475	520 b	6.2 bcd	1579 ab	6.4 N.S.	1661 ab
T_4	5282	150	525 b	6.5 cd	1594 abc	7.3 N.S.	1889 b
T_5	5282	341	735 c	6.7 d	2316 d	7.0 N.S.	2519 cd
T_6	5282	532	711 c	6.0 bc	2102 cd	7.6 N.S.	2686 d
T_7	6998	207	586 b	6.2 bcd	1794 abc	7.8 N.S.	2226 c
T_8	6998	475	741 c	5.7 b	2092 bcd	7.1 N.S.	2605 d
T_9	7733	341	674 c	5.1 a	1676 abc	6.4 N.S.	2236 c
$S_{\bar{x}}$ [5/]	-	-	27.3	0.15	129	-	83.5

1/ Includes 380 mm of water for establishment in 1982.
2/ Includes 55 kg/ha of nitrogen for establishment in 1982.
3/ Means followed by the same letter are not significantly different at the 5% level.
4/ No significant difference at the 5% level.
5/ Standard error of the means.

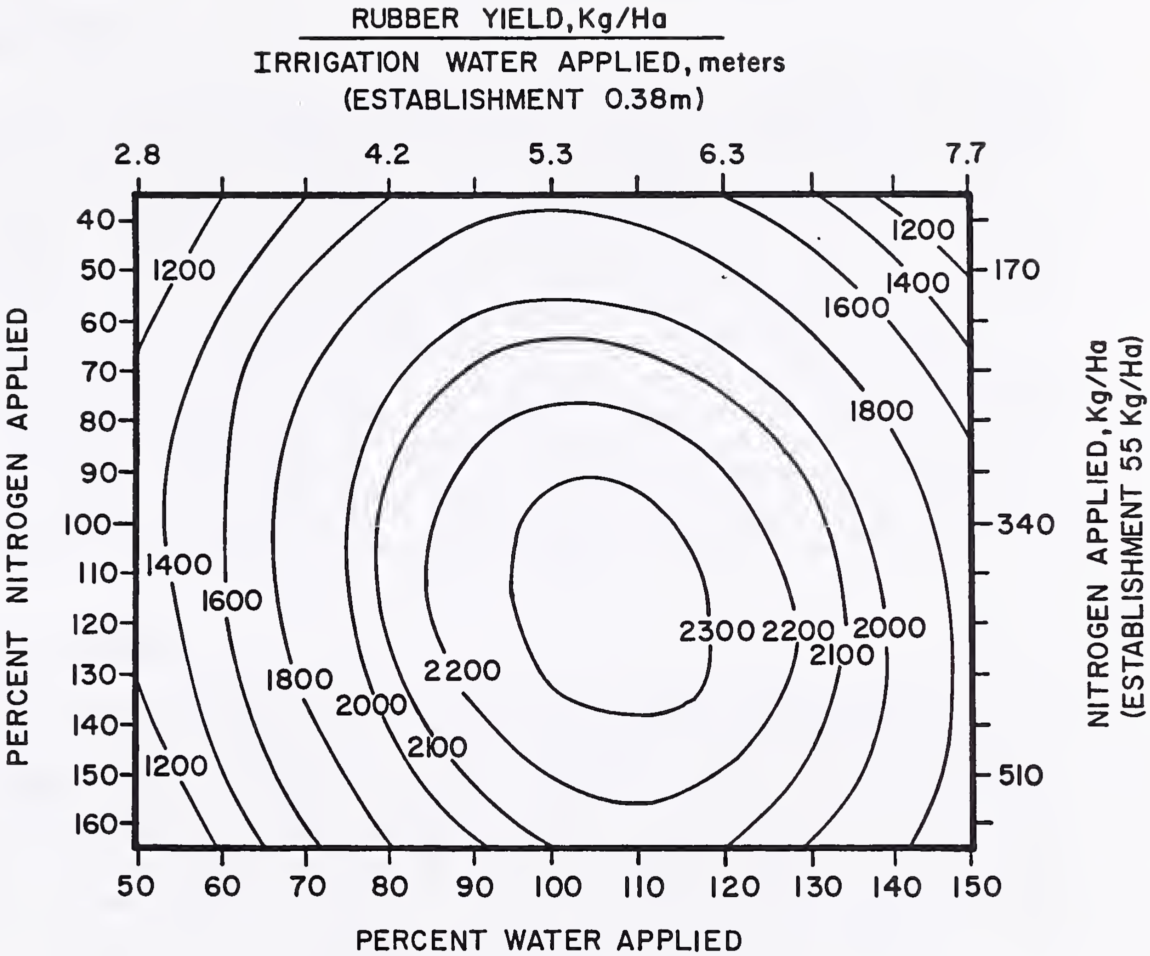

Figure 1. Rubber yield contours for non-bioregulator, whole plants harvested on January 23, 1985, and averaged for three guayule cultivars at Yume, AZ.

TITLE: WATER MANAGEMENT AND PRODUCTION RELATIONS OF MATURE GUAYULE

NRP: 20740 CRIS WORK UNIT: 5542-20740-012

INTRODUCTION

The successful cultivation of guayule (Parthenium argentatum Gray) in a non-native, semiarid environment provides numerous scientific and engineering challenges. Guayule, for rubber and resin production, has the potential of becoming a viable crop of agricultural, industrial and strategic importance in the United States and other countries. Both the search for renewable sources of energy-producing crops and the need for alternative crops to replace present surplus producing crops along with projected future water shortages continues to provide the incentive for renewed interest in guayule and other critical agricultural crops. However, knowledge on the water requirements and biotechnology responses that could be expected in the field have stymied various improvements in plant breeding technology and guayule commercialization. The objective of this report is to summarize rubber and resin production with four-year-old nonbioregulated and bioregulated guayule in central Arizona as it relates to water use, water requirements, and water stress behavior.

FIELD PROCEDURES

Three guayule cultivars (593, N565-II, and 11591) were started in the greenhouse and transplanted to the field in April 1981, at 54,000 plants/ha (22,000 plants/ac) at Mesa, Arizona. The site is on a uniform, medium water-holding capacity, loam soil; and the water contained 1.2 dS/m (800 mg/l) total dissolved salts. Six irrigation treatments, based on different percentages of soil water depletion in the crop root zone, were maintained using the level-basin irrigation method and replicated 4 times. Also, a portion of each plot was treated with 2 bioregulator compounds [2-(3,4-dichlorophenoxy)-triethylamine (A) and 2-(2,4-dichlorophenoxy)-triethylamine (B)] sprayed 4 times/year at concentrations of 100 mg/l for a total of 12 applications and at a concentration of 2000 mg/l at 6 months before harvest. Periodic soil water content and plant canopy temperatures as well as daily meteorological parameters were also measured.

Nonbioregulated whole plants for each cultivar-irrigation-replicate treatment were sampled approximately every 3 to 4 months from August 1981 to October 1984 for 14 harvests. Final harvesting of at least 30 nonbioregulated whole plants and 5 bioregulated whole plants for each individual sub-subplot was made in February 1985. Resin and rubber concentrations were determined from the defoliated plants for the first two years using the solvent extraction procedure; and concentrations and moisture content were analyzed for the last two years using the near infrared spectrophotometric (NIR) method, which was calibrated with the solvent extraction procedure.

RESULTS AND DISCUSSION

Data on the number and amount of irrigation water applied, evapotranspiration, and yields for the six irrigation treatments are presented for the three cultivars for the first two years, last two years, and final harvest in Table 1. The total measured evapotranspiration (ET) over the four years ranged from about 7040 mm (277 in) on the I_1 wet to 3245 mm (128 in) on the I_6 dry treatment, and the seasonal ET increased by approximately 25% for each additional year. The total ET closely matched the irrigation applications on the wettest treatments with a small quantity of water lost to deep percolation, whereas ET was greater than the water applied on the driest treatment with a more effective use of rainfall and stored moisture.

Statistical analysis of the rubber and resin yields at the final harvest for nonbioregulated whole plants showed nearly a linear decrease in total production from the I_1 (wet) to the I_6 (dry) treatment. Overall, the potential for rubber and resin production was greater during the last two years than the first two years (Table 1). At the final harvest, the higher rubber contents present on the drier treatments did not compensate for the lower amount of biomass as water applications became less; and resin concentrations were not significantly different among irrigation treatments. Rubber and resin yields related directly to seasonal evapotranspiration, average soil water content, and average crop water stress index. The linear regression equation for whole plant rubber yield (RUW, kg/ha) versus cumulative ET (mm) was RUW = 847.4 + 0.242 ET (R^2 = 0.87), as shown in Figure 1. When all irrigation treatments and harvest dates are considered, the water use efficiency (production divided by cumulative ET) for rubber yield typically ranged from about 0.035 to 0.045 kg/m^3 (110 to 150 lb/ac-ft), and for resin yield ranged from 0.040 to 0.055 kg/m^3 (110 to 150 lb/ac-ft) for three current guayule cultivars.

In terms of plant bioregulation, there were no significant differences in biomass, rubber and resin contents, and rubber and resin yields when averaged over the six irrigation treatments. Rubber yields are shown in Table 2. However, within irrigation treatments, there were some indications that bioregulation improved rubber and resin yields at the I_4 and I_5 (medium-dry) irrigation treatments. This could have occurred because fewer plants were available at final harvest from the bioregulated compared to nonbioregulated guayule.

SUMMARY AND CONCLUSIONS

The highly drought-tolerant guayule plant can be successfully grown with minimal water, but to achieve high biomass and yields in a short time, substantial supplemental water application is needed. Water management research at Mesa, Arizona, showed that the highest rubber and resin yields of 2530 and 3340 kg/ha, respectively, occurred on the wettest treatment with an evapotranspiration rate of 7040 mm over the four-year growth period. Water use efficiencies (production/unit of ET) generally

ranged from 0.035 to 0.045 kg/m^3 for rubber and 0.040 to 0.055 kg/m^3 for resin production depending on the water stress treatment and harvest date. Spray applications of bioregulators over the four years did not improve rubber or resin yields on the cultivars used in this field experiment. Environmental parameters such as available soil water content, evapotranspiration, and crop water stress index were found to be good predictors of rubber and resin yields. Guayule growth and survival can be maintained on less water; however, under intensified commercial farming, additional irrigation water will be needed to promote faster growth, earlier harvests, and ensure higher yields.

PERSONNEL

D.A. Bucks, F.S. Nakayama, O.F. French, and B.A. Rasnick (U.S. Water Conservation Laboratory); W.L. Alexander and D.E. Powers (University of Arizona).

Table 1. Water application, evapotranspiration, and rubber and resin yield and content data for four-year-old nonbioregulator whole guayule plants under six irrigation treatments averaged for three cultivars.

Period and Parameter	Irrigation Treatments					
	I_1	I_2	I_3	I_4	I_5	I_6
Final Harvest						
May 1, 1981–Feb 6, 1985[1/]						
No. irrigations	43	35	28	23	18	12
Irrigation amount (mm)	6958	5534	4726	3752	2952	1966
ET (mm)	7039	5809	5134	4390	3703	3243
Cumulative rubber yield (kg/ha)	2527a[2/]	2114c	2250b	1990cd	1818d	1471c
Rubber content (%)	5.3c	5.3c	5.8c	6.5a	6.0ab	5.9abc
Cumulative resin yield (kg/ha)	3343a	2853b	2808b	2214c	2097c	1611d
Resin content (%)	7.2N.S.[3/]	7.7N.S.	7.4N.S.	6.7N.S.	7.0N.S.	6.4N.S.
Cumulative dry matter yield (g/plant)[4/]	857a	690b	706b	612c	561d	465e

1/ Precipitation for first two years = 405 mm: for second two years = 590 mm.

2/ Values followed by the same letter in each row belong to the same population at the 5% level of significance according to the Duncan's Multiple Range Test.

3/ Analysis of variance showed no significant differences.

4/ g/plant x 54 ≅ metric tons/ha.

Table 2. Rubber yield data on two bioregulator and nonbioregulator treatments for four-year-old whole guayule plants under six irrigation treatments averaged for three cultivars.

Period and Bio. Treatment	Irrigation Treatments						
	I_1	I_2	I_3	I_4	I_5	I_6	All
Final Harvest May 1, 1981-Feb 6, 1985							
Bio. A	2419	1887	2100	2309	2063	1503	2046 N.S.[1/]
Bio. B	2614	1983	2364	2213	2007	1439	2103 N.S.
Check	2527	2114	2250	1990	1818	1471	2028 N.S.

[1/] Analysis of variance showed no significant difference.

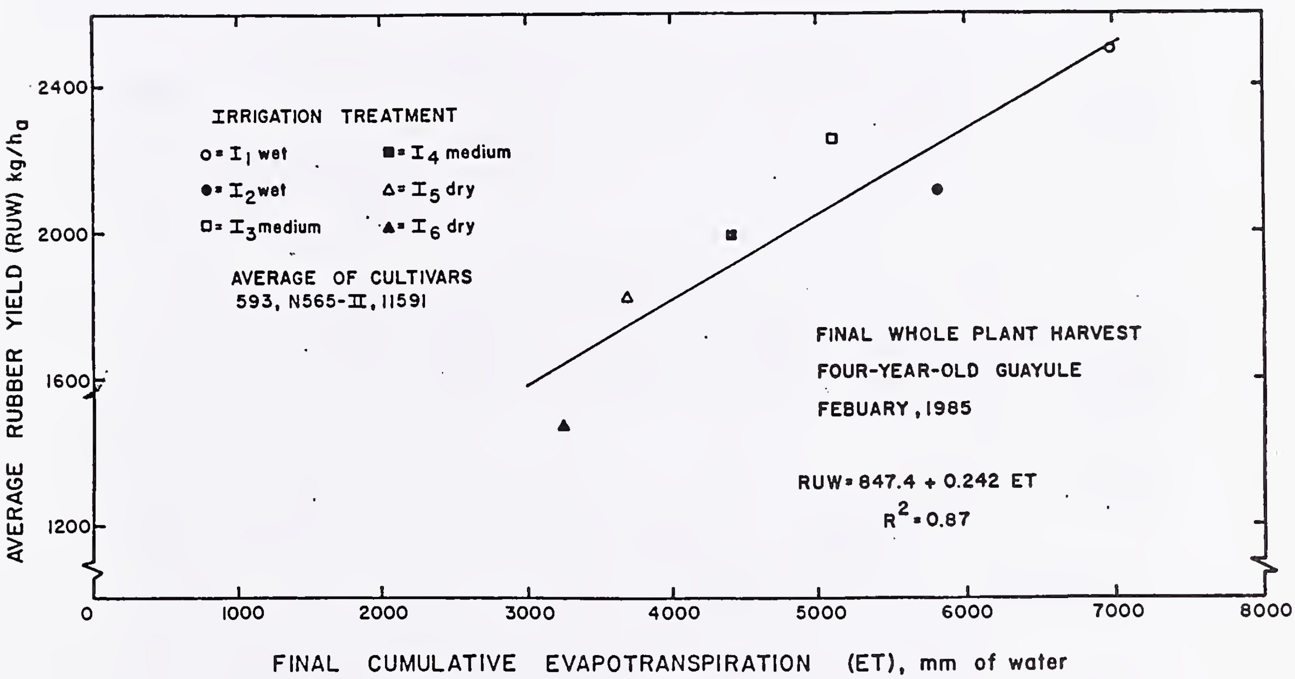

Figure 1. Relationship between the average rubber yield and cumulative evapotranspiration at the final, four-year harvest of three guayule cultivars under six irrigation treatments at Mesa, Arizona.

TITLE: SOIL-WATER-PLANT RELATIONSHIP OF DROUGHT-TOLERANT CROPS IN ARID ENVIRONMENTS

NRP: 20760 CRIS WORK UNIT: 5542-20760-002

INTRODUCTION

This project was terminated in 1985. No research was done on it, but the three field sites (Granite Reef, Usery Pass and Camp Verde) had to be dismantled and restored to cooperator specifications. Several manuscripts reporting unpublished data are in various stages of preparation (see LIST OF 1985 PUBLICATIONS).

A new CRIS project titled, "Seedling Establishment of New Crops Under Crusting and Other Limiting Soil Related Conditions," has been submitted for approval. Some research on the new CRIS has been started and some of the equipment required for such research has been purchased or constructed.

In this USWCL Annual Report some of the major conclusions gleened from the runoff-farming study with Christmas trees are summarized, and preliminary research findings from the new study are presented.

Conclusions From the Runoff-Farming for Christmas Trees Production Study

1. Runoff-farming can be used to successfully grow Christmas trees in the arid Southwest. Irrigation is not required.
2. Marginal land and land without irrigation water rights can be used.
3. Small farmers should be able to utilize the techniques we developed to supplement their incomes.
4. Christmas trees are a low-risk crop for runoff-farming because they are drought tolerant.
5. Christmas trees are a low water requiring crop: 2 feet per year at maturity, and less during establishment.
6. Groundwater recharge occurs using runoff-farming for this crop because (a) excess runoff is generated during the tree establishment years, and (b) catchment size must be overdesigned to assure crop survival and even quality growth in years (50%) with below normal precipitation.
7. Christmas trees can attain marketable size in 3 to 4 years in the Southwest using runoff-farming compared to 5 to 10 years normally required for trees grown in the northern climates.
8. Christmas trees are a potential new crop for the arid Southwest. Unlike most proposed new crops, consumer demand and a complete local marketing structure already exists for Christmas trees.
9. Trees grown locally in the Southwest should be fresher and have lower shipping costs compared to imported trees. Hence, demand should be greater and profits higher.

Seedling Establishment of New Crops

Several new crops have been proposed to improve the economic conditions of U. S. farmers and meet changing product demands. Little is known about the cultural practices required to grow many of these crops. Trouble in anticipated with all aspects of production, but particularly so with the critical establishment phase. This is because most of these crops have small low-vigor seeds with a variety of adaptations for survival in the wild, but which adaptations generally prove troublesome under cultivation.

The seedling emergence-crop establishment process may be divided into three integrally related aspects: (1) the seed, (2) the soil, and (3) the seeding operation. Research is needed on the seed to improve germination and vigor (rate and uniformity of germination, early growth and emergence, and resistance to disease). Research is needed on improving the soil environment surrounding the seed/seedling. The stresses of water, salt, temperature, aeration, and mechanical impedance must be understood and overcome. Seeding techniques and equipment must be developed for these new crops.

Research must proceed on all three aspects if the problems of crop establishment are to be solved. The preliminary results reported here concern seed/seedling vigor testing of guayule as determined using the slant plate method. Two cultivars, N565-II and 11591 (conditioned and unconditioned) were evaluated. Twenty seeds were placed in a straight line on the blotter paper, one inch down from the top of each plate. There were four replications. Three temperature regimes were evaluated: 5N-15D, 10N-20D, and 15N-25D, where N and D are night and day (dark and lighted), respectively. Temperature and light were cycled every 12 hours. Germination and root/shoot growth were evaluated daily.

Germination results for the 10N-20D regime are shown in Figure 1. Open symbols represent total germination (shoot and/or radical protrusion greater than 2 mm), while the closed symbols on the last day represent the percent of normal germinated seeds. The notation T-50 and T-80 represent the number of days to 50 and 80 percent germination of those seeds that germinated.

The T-% data are summarized in Table 1 for the three temperature regimes. Several things are apparent. Conditioned seed gets off to a faster start than irrigated seed -- particularily at low temperatures. Initiation of germination of conditioned seed was only 1 or 2 days ahead of unconditioned seed at the two higher temperature regimes but was a week ahead at the low temperature. Time to 80% germination increased from 2 to 12 days (10 day increase) for the 11591C from highest to lowest temperature regimes, but increased from 4 to 21 days (17 days increase) for cv. 565.

Table 2 shows that optimum germination occurred at the 10N-20D temperature regime. Germination of cv. 565 was low throughout but dropped

to only 4% normal seedlings at the 5N-15D temperature regime. Conditioning improved all aspects of germination and vigor of cv. 11591. No conditioned cv. 565 was available for testing.

The next phase of these studies will be to evaluate vigor of the seedlings in soil under various regimes of temperature, water and salt stress, and as a function of planting depth to determine mechanical strength of the emerging seedlings. This information should in turn aid in developing improved direct seeding techniques for field planting.

SUMMARY

This project was terminated in 1985. No research was done on it, but the three water harvesting/runoff-farming field sites were dismantled and restored to the cooperator's specifications. Several manuscripts reporting unpublished data from the project are in various stages of preparation. A new CRIS titled, "Seedling Establishment of New Crops Under Crusting and Other Limiting Soil Related Conditions", was submitted for approval. Research on the new project has begun and some of the specialized equipment required has been borrowed, built, or purchased. Preliminary research results on evaluating seedling vigor using the slant plate technique suggests that, for guayule, both germination and vigor are optimal at a temperature regime of 10C night/20C day (12 hr cycles), and that conditioning seed to enhance vigor is particularly benefical at low temperatures.

PERSONNEL

D. W. Fink

Table 1. Time to initiation (T-0), 50% (T-50) and 80% (T-80) germination of those seeds which germinated for guayule cvs. N-565-II, 11591 and conditioned 11591 at three temperature regimes.

Germination/Vigor - (Guayule)			
Treatment/Measurement	565	11591	11591C
	---------- days ----------		
5N-15D			
T-0 (days)	9	9	2
T-50 "	12	14	7
T-80 "	21	17	12
10N-20D			
T-0 (days)	2	3	<1
T-50 "	4.7	5.6	2.9
T-80 "	6.3	7.4	5.5
15N-25D			
T-0 (days)	1	1	<1
T-50 "	3	3	1
T-80 "	4	4	2

Table 2. Germination/vigor of guayule at three temperature regimes using the slant plate technique.

Germination/Vigor - (Guayule)			
Treatment/Measurement	565	11591	11591C
	---------- % ----------		
5N-15D (24 days)			
Germination	11	50	64
Normal	4	42	46
Dead or ungerminated	89	50	36
Abnormal/germinated	60	19	26
10N-20D (16 days)			
Germination	26	76	84
Normal	24	69	76
Dead or ungerminated	74	24	16
Abnormal/germinated	8	9	10
15N-25D (10 days)			
Germination	25	58	64
Normal	16	42	50
Dead or ungerminated	75	42	36
Abnormal/germinated	37	28	22

TITLE: SOIL-PLANT-ATMOSPHERE INTERACTIONS AS RELATED TO WATER CONSERVATION AND CROP PRODUCTION

NRP: 20760 CRIS WORK UNIT: 5422-20760-003

INTRODUCTION

1985 was another good productive year for our research group. Because we are time and cost conscious, only the most significant of our publications are included in this year's report, as well as experiments not quite yet completed. We had 39 papers published, 18 are in press, and 15 are in the journal review process. Again, there are numerous manuscripts in all stages of completion, and you'll be reading about many of them next year in our annual report.

Two papers deal with the assessment of stomatal and canopy resistances of field grown wheat. The first paper uses measurements of leaf water potential, stomatal resistance, canopy temperature and evapotranspiration flux to calculate plant and canopy resistances. A little different approach is used in the second paper where an empirical model for stomatal resistance is developed from measurements of net radiation and leaf water potential. Three other papers, also on our wheat crop, are concerned with factors affecting the measurement of reflectance. Cultivar differences in canopy architecture, not differences in specific leaf reflectance, were shown, in two papers, to significantly affect overall canopy reflectance, and that multiple sun angle data acquisitions might be required to assess green leaf area and biomass. The third paper, which considered the effect of dew on canopy reflectance, established that moderately high dew levels increased, decreased or had no effect on reflectance depending on the wavelength region of interest. Another paper on wheat showed that total above-ground phytomass determined from remotely sensed data was well correlated with measured values.

One paper was concerned with measuring the spatial variability of evaporation of water from bare soil using reflected and emitted radiation from the surface and routine meteorological parameters. This study was to investigate the spatial variability of evaporation over a relatively small field plot. Two studies were aimed at the absolute calibration of remote sensing instruments. The first technique uses a standard reflectance plate placed horizontal to the surface, and is alternately exposed to the sun and shade. More sophisticated methods are explained in the second paper.

Another pair of papers deals with effects in increasing concentration of atmospheric carbon dioxide on climate and plant behavior. A broad look at the CO_2 picture indicates that the first detection of the increased CO_2 level has been observed in an increase in photosynthetic activity

and not in an increase in global climate. At a lower level of observation, the second paper demonstrates that, in field experiments, a doubling of CO_2 increased water hyacinth biomass by about one-third, and decreased transpiration by a like amount, which resulted in a doubling of the water use efficiency.

Four other papers, on differing subjects, are worthy of note. First, is a comparison of model and empirical studies, which agree that the mean global surface temperature could warm by no more than 4 or 5 K. The second study, by a visiting scientist from New Zealand, demonstrated that soil heat flux could be estimated as a fraction of the net radiation, depending on the amount of vegetation and the time of day. A third paper, from a visiting graduate student's dissertation, revealed that the leaf appearance rate of wheat could be estimated from a relationship between growth stage and accumulated thermal units. The last paper, also from another graduate student's thesis, evaluated the effect of topography, slope and aspect, on the microclimate, growth and yield of barley grown in the Dunnigan Hills of California for the HCMM project.

Two experiments were conducted on the University of Arizona Maricopa Agricultural Center (MAC farm) using remote sensing techniques. One dealt with investigating the spatial variability of wheat canopy temperature in long borders. Although the analysis of the data is continuing, preliminary indications are that the use of canopy temperature variability to schedule irrigations may not be as easy as was first proposed. A multi-level observations experiment to assess evapotranspiration from bare soil and cropped surfaces is the focal point of the second experiment. Measurements from the ground, aircraft and satellite correlate well with on-the-ground Bowen Ratio observations of evapotranspiration. This work will continue in 1986.

A project to evaluate the possibility of using plastic cylinders as transfer standards for neutron probe calibrations is described. It was found that these standards could be used between probes with like detectors, but they were not adequate where the detectors were different. Yet another study was started to evaluate the use of resistance blocks to schedule irrigations, and to compare this technique with the Crop Water Stress Index obtained from infrared thermometer measurements of canopy temperature. Preliminary results are presented. Measurements taken during the second year of our alfalfa experiment in the lysimeter field are described. A few mini-experiments that have been ongoing throughout the year are explained, as well as other observations, such as the incidence of pests.

CANOPY RESISTANCE

Choudhury, B.J. and Idso, S.B. Evaluating plant and canopy resistances of field-grown wheat from concurrent diurnal observations of leaf water

potential, stomatal resistance, canopy temperature, and evapotranspiration flux. Agric. For. Meteorol. 34:67-76.

Concurrent observations of leaf water potential, stomatal diffusion resistance and canopy temperature were made on two plots of wheat (Triticum aestivum L. cv. Anza) growing at Phoenix, Arizona under two different soil water conditions. These data were further complemented by weather observations and lysimeter measurements of total evaporative water loss from the plots. Transpiration fluxes for each plot were estimated by an aerodynamic-energy balance approach and compared with the lysimeter data. Plant resistances were computed from the transpiration flux results and the leaf water potential measurement using van den Honert's equation, while canopy resistances were also computed from the transpiration flux using Monteith's equation. The calculated plant resistance decreased by a factor of almost two from morning to mid-afternoon whereas the ratio of canopy and stomatal resistances were constant during most of the day.

Choudhury, B.J. and Idso, S.B. An empirical model for stomatal resistance of field grown wheat. Agric. For. Meteorol. 36:65-82.

From concurrent data of stomatal conductance of sunlit leaves (C_l; mm s^{-1}), leaf water potential (ψ; m), and net radiation (R_n; W m^{-2}) we derive the empirical relationship:

$$C_l = (0.986 + 0.025\ R_n) \left[\frac{1}{1+(\psi/-230.8)^{5.51}}\right]$$

Stomatal conductances calculated using the above equation are compared with an independent data set. Canopy resistance derived from the above equation is used in a plant water balance equation to simulate diurnal evaporation fluxes for three days, and we compare the calculated fluxes with lysimeter observations for well-watered and water-stressed wheat. Canopy temperatures are additionally obtained from an energy balance equation and compared with infrared radiometer observations. Regression analysis of simulated and observed evaporation fluxes yields a correlation coefficient of 0.98 and a standard error of estimate of about 37 W m^{-2}; while for the canopy temperatures the correlation coefficient is 0.98 and the standard error of estimates 1.04°C. Variation of canopy net photosynthesis with insolation, and leaf area index are also simulated and compared with observations.

CROP REFLECTANCE

Jackson, R.D. and Pinter, P.J., Jr. Spectral response of architecturally different wheat canopies. Remote Sensing of Environment. (In press).

The spectral response of two architecturally different spring wheat canopies having similar single leaf reflectance, green leaf area index (GLAI), and total dry phytomass was measured throughout a growing season. Experimental results and supporting model calculations showed that the more planophile canopy had a higher spectral reflectance (measured at nadir) than the erectophile canopy. During the period of peak GLAI, the ratio of near-infrared to red reflectances (IR/red) for the erectophile canopy was about 30% higher than for the planophile canopy. The perpendicular vegetation index (PVI), however, was about 30% higher for the planophile canopy than for the erectophile canopy. When ground measured reflectances were transformed to radiances exiting the top of either a clear or a turbid atmosphere, the differences between the erectophile and the planophile canopies remained for the PVI but were obscured for the IR/red ratio. The results demonstrate the importance of architectural effects on the spectral response of canopies, and the interpretation of that response for estimating GLAI and dry phytomass by use of vegetation indices.

Pinter, P.J., Jr., Jackson, R.D., Ezra, C.E. and Gausman, H.W. Sun angle and canopy architecture effects on the spectral reflectance of six wheat cultivars. Int. J. Remote Sensing 6:1813-1825.

Canopy spectral reflectances were measured over six cultivars of spring wheat (Triticum aestivum L.) grown at Phoenix, AZ. Data were collected at 30 to 45 minute intervals on 9 March 83 using two ground-based radiometers with bandpass characteristics similar to those of the multispectral scanner and thematic mapper on Landsat 4 and 5. Major differences in reflectance were observed among cultivars at every time period despite their apparent similarities in green leaf area and green biomass. Single-leaf spectra measured in the laboratory with a spectrophotometer revealed no cultivar-related differences and supported the contention that the reflectances were strongly influenced by canopy architectural features. The diurnal patterns of reflectance reinforced this conclusion with planophile canopies exhibiting the least amount of variability due to changes in sun angle and erectophile canopies showing the most. These data underscore the complexities of interpreting remotely sensed multispectral data and suggest that multiple sun angle data acquisitions may be required to extract desired information.

Pinter, P.J., Jr. Effect of dew on canopy reflectance and temperature. Remote Sensing of Environment. (In press)

The diurnal behavior of canopy reflectance and emittance was characterized for six spring wheat cultivars using two ground-based radiometers that had spectral bandpass characteristics similar to the multispectral scanner and thematic mapper radiometers on Landsat 4 and 5. Nadir measurements of spectral reflectance and emittance were made over well-watered canopies with and without dew to determine its effect on

each wavelength interval. The diurnal patterns of reflectances from canopies without dew were symmetric with respect to solar noon. However, when dew was present on canopies, morning reflectances in wavelengths shorter than 0.7 μm and longer than 1.15 μm were significantly different than those observed during the afternoon under similar solar zenith angles. Quantitative measurements of dew density in each cultivar established that moderately high dew levels increased reflectance in visible wavelengths by 40 to 60%, and decreased reflectance in wavelengths between 1.15 and 2.35 μm by 25 to 60%. No effect of dew was noted in the near-IR region of the spectrum between 0.7 and 1.1 μm or the thermal IR (10.4 to 12.5 μm).

Asrar, G., Kanemasu, E.T., Jackson, R.D. and Pinter, P.J., Jr. Estimation of total above-ground phytomass production using remotely sensed data. Remote Sensing of Environ. 17:211-220.

Remote sensing potentially offers a quick and nondestructive method for monitoring plant canopy condition and development. In this study, multispectral reflectance and thermal emittance data were used in conjunction with micrometeorological data in a simple model to estimate above-ground total dry phytomass production of several spring wheat canopies. The fraction of absorbed photosynthetic radiation (PAR) by plants was estimated from measurements of visible and near-infrared canopy reflectance. Canopy radiation temperature was used as a crop stress indicator in the model. Estimated above-ground phytomass values based on this model were strongly correlated with the measured phytomass values for a wide range of climate and plant-canopy conditions.

EVAPORATION

Rice, R.C. and Jackson, R.D. Spatial distribution of evaporation from bare soil. Proc. of the National Conference on Advances in Evapotranspiration, ASAE, Chicago, IL, 16-17 Dec. 1985. pp. 447-453.

Deep percolation of excess irrigation water must be determined to predict the effect of irrigation on groundwater and to develop irrigation strategies to minimize undesirable effects. Deep percolation rates vary considerably over a field due to soil type, non-uniform water application, changes in soil properties over the growing season and quality of applied water. Deep percolation rates are often calculated as the residual in the water balance equation. The evaporation component in the energy balance equation is usually estimated from meteorological data obtained from one location in the field and then applied to the entire field. Recent studies using tracers demonstrated the feasibility of making point measurements of deep percolation rates (Bowman and Rice 1984). However, when point measurements are made, some idea of the spatial structure of evaporation is needed if the measurements are to be extrapolated over the entire field. Evaporation from bare soil can be

expected to be rather uniform under energy limiting conditions (wet soil) and soil limiting conditions (dry soil) (Jackson et al., 1976). However, during the transition phase when some portions of the field are wetter than others, evaporation rates will vary considerably over the field. Vauclin et al. (1982), studied the spatial variability of surface temperatures over bare soils. Their semivariogram and autocorrelation functions were found to be correlated over space. Hatfield et al. (1984), found no spatial structure for surface temperatures measured on an irrigated sorghum field suggesting that random measurements would be adequate to characterize the field. They also found that the variance of the surface temperatures increased during a drying cycle. Recent advances in remote sensing techniques now permit estimates of instantaneous evaporation rates (Jackson 1984) which can be used to determine evapotranspiration at a number of points within a field in a short time period. The object of this study is to use these remote sensing approaches to determine the spatial variability of evaporation from a bare soil during the energy limiting, transitional, and soil limiting phases of evaporation.

RADIOMETER CALIBRATION

Jackson, R.D. and Slater, P.N. Absolute calibration of field reflectance radiometers. Photogrammetric Engineering and Remote Sensing. (In press)

A method is described whereby field reflectance radiometers can be calibrated in an absolute sense using equipment available at most agricultural or environmental research locations. A radiometer is positioned directly above a calibrated standard reflectance panel that is horizontal to the earth's surface. The sun's direct beam is separated from the global irradiance by alternately exposing and shading the panel periodically from shortly after sunrise to near solar noon. A graph of the logarithm of the radiometer response versus the secant of the solar zenith angle (known as the Langley plot) yields the spectral-extinction optical thickness of the atmosphere as the slope and the logarithm of the exoatmospheric irradiance divided by the calibration factor as the intercept. Calibration factors for two radiometers agreed to within 10% with factors obtained by other methods, indicating that this technique is a viable and simple method for the absolute calibration of field radiometers.

Biggar, S.F., Bruegge, C.J., Captron, B.A., Castle, K.R., Dinguirard, M.C., Holm, R.G., Jackson, R.D., Mao, Y., Moran, M.S., Palmer, J.M., Phillips, A.L., Savage, R.K., Slater, P.N., Witman, S.L. and Yuan, B. Absolute calibration of remote sensing instruments. Proc. 3rd Intern. Colloquium on Spectral Signatures of Objects in Remote Sensing. (In press)

Source-based and detector-based methods for the absolute radiometric calibration of a broadband field radiometer are briefly described. Using such a radiometer, calibrated by both methods the calibration of the integrating sphere used in the pre-flight calibration of the Thematic Mapper was re-determined. The results are presented.

The in-flight calibration of space remote sensing instruments is briefly discussed. A method is described which uses the results of ground-based reflectance and atmospheric measurements as input to a radiative transfer code to predict the radiance at the instrument. A calibrated, helicopter-mounted, radiometer is used to determine the radiance levels at intermediate altitudes to check the code predictions. Results of such measurements for the calibration of the Thematic Mapper on Landsat 5 are described together with an analysis that shows the value of such measurements.

CO_2, CLIMATE, AND PLANTS

Idso, S.B. The search for global CO_2 etc. 'Greenhouse effects.' Environ. Conservation 12:29-35.

The concentration of carbon dioxide (CO_2) in Earth's atmosphere has been steadily increasing since the inception of the Industrial Revolution. Believed to be due primarily to the burning of fossil fuels and the clearing of forests, this phenomenon has two potential consequences of global importance.

Many scientists believe that the CO_2 increases projected for Earth's atmosphere by the middle of the next century will lead to a significant warming of the planet which could severely impact world agriculture and cause a melting of polar ice which would greatly raise sea-levels and lead to the flooding of coastal lowlands. Others, however, point to the demonstrable positive effects of elevated concentrations of atmospheric CO_2 on plant productivity and water-use efficiency, suggesting that more CO_2 in the air will be beneficial to The Biosphere. Against this backlog of controversy, scientists of both persuasions have attempted the 'first detection' of either or both of these effects on a global scale.

With respect to the quest for a climatic 'signal,' numerous studies conducted to date have come up empty-handed; it is just not discernible from the natural variations inherent in the data. However, there does appear to be a manifestation of enhanced global photosynthetic activity in the yearly amplitude of atmospheric CO_2 concentrations at a number of sites around the world; and the most logical explanation of that seems to be the CO_2-induced enhancement of plant growth and development which has been demonstrated to occur in hundreds of laboratory and field experiments.

The upshot of those observations relative to the CO_2 'problem' is that it may not be a problem at all, but rather a blessing in disguise. Nevertheless, further careful scrutiny of both aspects of the issue are clearly warranted, particularly in view of the magnitude of the potential consequences.

Idso, S.B., Kimball, B.A. and Anderson, M.G. Atmospheric CO_2 enrichment of water hyacinths: Effects on transpiration and water use efficiency. Water Resources Research 21:1787-1790.

Open-top clear-plastic-wall chambers enclosing pairs of sunken metal stock tanks, one of each pair of which contained a full cover of water hyacinths, were maintained out-of-doors at Phoenix, Arizona for several weeks during the summer of 1984. One of these chambers represented ambient conditions, while the other three were continuously enriched with carbon dioxide to approximate target concentrations of 500, 650 and 900 ppm. During a four-week period when plant growth was at its maximum, water hyacinth biomass production increased by 36% for a 300 to 600 ppm doubling of the atmospheric CO_2 content; while water use efficiency, or the biomass produced per unit of water transpired, actually doubled. These results are similar to what has been observed in several terrestrial plants; and they indicate the general trend which may be expected to occur as atmospheric CO_2 continues to rise in the years ahead.

AIR TEMPERATURE

Idso, S.B. An upper limit to global surface air temperature. Arch. Met. Geoph. Biocl., Ser. A, 34:141-144.

Several empirical studies of Earth's surface air temperature and radiation budget have indicated that there is an upper limit above which the mean surface air temperature of the globe cannot rise, as long as the solar constant and the mass of Earth's atmosphere remain unchanged. It is shown that current state-of-the-art climate models suggest the same thing and that they yield a comparable value for the maximum warming attainable: 4-5 K.

SOIL HEAT FLUX

Clothier, B.E., Clawson, K.L., Pinter, P.J., Jr., Moran, M.S., Reginato, R.J. and Jackson, R.D. Estimation of soil heat flux from net radiation during the growth of alfalfa. Forest and Agricultural Meteorology. (In press)

Soil heat flux studies have indicated that the instantaneous daytime flux can be estimated as a fraction of the net radiation; the ratio ranging from 0.1 to 0.5, depending on the amount of vegetation present

and on the time of day. Soil heat flux and net radiation were measured for an alfalfa crop over two regrowth cycles during the fall growing season. For both sparse alfalfa stubble and full vegetative canopy, the surface soil water content did not significantly affect the fraction of net radiation consumed as soil heat flux. The ratio of soil heat flux to net radiation around midday was found to be a linearly decreasing function of crop height only for heights up to 450 mm. As crop growth continued beyond this height, the ratio remained nearly constant at 0.1. The ratio data were also found to be well-fitted by a linearly decreasing function of a spectral vegetation index (near-IR to Red ratio) over both regrowth cycles. These results indicate that both crop height and spectral vegetation indices can be used to estimate soil heat flux from net radiation measurements.

PLANT GROWTH

Baker, J.T., Pinter, P.J., Jr., Reginato, R.J. and Kanemasu, E.T. Effects of temperature on leaf appearance in spring and winter wheat cultivars. Agronomy Journal. (In press)

An understanding of the genetic and environmental factors affecting the leaf area of a cereal crop is needed for accurate yield predictions by crop models. Field trials were conducted with three cultivars of winter wheat (*Triticum aestivum* L. em. Thell) at Manhattan, KS under dryland and irrigated conditions and with six cultivars of irrigated spring wheat at Phoenix, AZ in 1982 and 1983, respectively. Because leaf growth is strongly influenced by temperature, the rate of leaf appearance was expressed as leaves/thermal unit

$$(Tu = [TMAX + TMIN]/2 - T_b)$$

where Tu is thermal units, TMAX and TMIN are maximum and minimum daily temperatures, respectively and T_b is the base temperature below which growth essentially ceases. The T_b, determined for three winter wheat cultivars, was not significantly different from 0°C ($P \leq 0.05$). Phyllochron interval (PI), the inverse of leaf appearance rate, was determined from the slope of the regression of Haun scale growth units against accumulated Tu. The R^2 values for these regressions were not less than 0.97 nor 0.99 for spring and winter wheat cultivars, respectively. The PI was shorter for non-irrigated than irrigated winter wheat leaves ($P \leq 0.01$) and for spring wheat leaves formed prior to double ridges than those formed later ($P \leq 0.01$). Differences in PI were found among both spring and winter wheat cultivars ($P \leq 0.05$). These results illustrate the importance of determining PI for quantifying growth characteristics that determine the leaf area of a cereal crop.

Whitman, C.E., Hatfield, J.L. and Reginato, R.J. Effect of slope position on microclimate, growth and yield of barley. Agronomy J. 77:663-669.

Analyses of the relationship between microclimatic data, yield and growth response usually have been conducted utilizing data collected on level terrain and in small experimental plots. A field study was conducted on 290 ha of undulating topography of a Sehorn-Balcolm complex soil (Entic Chromoxeret and Typic Xerochert) near Dunnigan, CA (38°48'N 121°58'W) during 1977-78 to evaluate the effect of slope position and microclimate differences on the growth and yield of barley (Hordeum vulgare L. cv. Briggs). The crop was planted on 3 to 9 Dec. 1977 at 112 kg Ha^{-1} density in a 0.15-m row spacing. Sixteen sites were selected in the field prior to planting ranging from level to 36% slope with aspects from north- to south-facing slopes. At each site twice-weekly measurements were made of plant growth, i.e., height, number of green leaves, leaf area, number of tillers, dry weight,, and phenological stage, on 10 randomly selected plants. Yield and all yield components were measured on 20 1-m^2 samples at each site at the end of the experiment. Microclimatic data were measured at each site. The largest variations in crop development occurred prior to jointing and after anthesis. Both drainage and irradiance had large effects on plant growth, exhibited through differences in plant height, maximum leaf area, tiller survival, green leaves per plants, tillers per plant, relative growth rate, and dry matter production. A linear relationship was found between dry weight at the end of the season and intercepted radiation with a slope of 1.28 g MJ^{-1}. Dry matter production and yield were affected by irradiance and drainage. The date of 50% heading was inversely related to the final yield and suggested that delayed flowering was detrimental to grain production in the dryland conditions of the Central Valley.

MARICOPA AGRICULTURAL CENTER

Wheat Canopy Temperatures.

During the spring of 1985, a study to observe wheat canopy temperatures planted in long borders was initiated. The purpose of the experiment was to monitor the canopy temperature variability of long borders and relate the variability to such parameters as yield and water use. To insure that the variability observed was a function of water stress and not of weather variability (windspeed in particular), a companion study on the relation of variability associated with different recorder integration times was also undertaken. Long recorder integration times would smooth the rapid canopy temperature fluctuations caused by wind and allow for separation of water-stress- and windspeed-induced variability. Also undertaken was a companion study to evaluate the combined effects of solar irradiance angles and IRT view angles on measured wheat temperatures.

Methods and materials. The experiment was conducted at the University of Arizona Maricopa Agricultural Experiment Station in 1985. Complete

details of the cultural practices are found in the report on "Crop yield and water requirements as affected by spatial variations of soil, water quality, and irrigation amount" by D. J. Hunsaker et al. Briefly, the field was seeded to durum wheat (Triticum durum cv. Aldura) in the fall of 1984 in 12 borders 13.7 m wide by either 183 or 244 m long. Three different seasonal irrigation amounts were applied to the borders which were designated Wet, Medium, and Dry. The Wet treatment was designed to have 100% of expected evapotranspiration (ET) returned by irrigation, while Medium and Dry were designed to have only 75 and 50% of ET returned by irrigation, respectively. Of the 12 borders, only 4 were monitored for canopy temperature.

Canopy temperature observations began after ground cover reached 100% when observed obliquely. Measurements of canopy temperature were made at each access tube location in plots 9-12 using an infrared thermometer (IRT) held at a declination angle of about 30° from the horizontal. The plots were designated Dry, Dry, Medium, and Wet, respectively. Six different temperatures were recorded at each access tube site by pointing the IRT from the southern berm north toward the center of the border. The six temperatures thus recorded were then averaged to give a mean canopy temperature at each access tube. Measurements began in plot 12 (Dry) at tube 146 to tube 156, continued then in plot 11 (Dry) at tubes 131 to 145, then in plot 10 (Medium) at tubes 116 to 130 and concluded in plot 9 (Wet) at tubes 101 to 115. Thus, a total of 56 sites were monitored by the IRT. Psychrometric measurements preceded and followed each series of temperature measurements. The day of the year on which measurements were made, together with the number of complete observation cycles for that day (in parenthesis) are: 73 (2), 77 (4), 84 (2), 91 (4), 98 (4), 105 (4), 108 (3), 113 (4), 123 (2), 126 (7), 148 (4).

In addition to canopy temperature measurements, micrometeorological variables were measured every minute with a Campbell Scientific CR-21 micrologger. These variables were air temperature, relative humidity, solar radiation and windspeed, all at a height of 2 m. On day 148, a net radiometer was also installed.

To account for windspeed variability and to observe the effects of instrument view direction, two small plots (each 45 x 45 ft) adjacent to the large field were identified for intensive measurements. One plot was maintained under well-watered conditions, while the second plot received no supplemental irrigation. Plant growth in the latter plot was severely stunted, a result of severe water stress. Canopy temperature measurements were made of the center of each of these plots several times during the day from the four cardinal compass directions, i.e., north, south, east, and west. A fast reading (25 ms in duration) followed immediately with a slow reading (10 s in duration) of the same target was recorded. Thus for each view direction, the mean of 6 fast and the mean of 6 slow readings were recorded. All other specifics

associated with this companion study were the same as that specified for measurements in the large plots. The day of the year and number of complete observations for each day (in parenthesis) on which these measurements were made are: 84 (3), 91 (7), 98 (7), 102 (1), 105 (6), 108 (2), 113 (7).

Results and discussion. Analysis of the data is continuing. A brief discussion of the results is presented here. Solar-instrument azimuth effects on observed canopy temperature were not observed in this study as they have been for other crops such as alfalfa and soybeans. Regression analysis indicated a lack of any significant relationship ($P<-0.05$). Because of this fact, the IRT can be pointed in any direction and an average canopy temperature for wheat can be obtained without regard to the location of the solar disk.

Windspeed variability was also found to have no effect on the observed average canopy temperature. For the 62 time periods analyzed, the mean canopy temperature obtained from a 25 ms recorder integration time was 31.4°C while the mean canopy temperature obtained from a 10 s recorder integration time was 31.3°C. An analysis of variance showed that the two means were not significantly different from each other ($P<-0.05$). Thus, any water stress index which required average canopy temperature as an input, can be used with the assurance that the resulting output is independent of windspeed.

Windspeed variability did, however, cause the standard deviation of the mean canopy temperature to be greater. The average standard deviation of the mean temperature recorded at 25 ms was 0.82 while at 10 s it was 0.67. An analysis of variance of these data indicated that this difference was small but indeed significant ($P<-0.05$). It can be concluded that any water stress index which requires a measure of the variability of canopy temperatures must inevitably be interpreted in light of windspeed variability.

Variability within a border was found to be a function of water stress as indicated by an analysis of variance of the large field data. Mean standard deviations for the Wet, Medium and two Dry plots were 0.48, 0.60, 0.88 and 0.89, respectively, and were significantly different from each other ($P<-0.01$). From this, it can be concluded that well-watered plots have a small but significant variability in measured canopy temperature. This "baseline" variability increases with increasing water stress as indicated by the increase in the mean standard deviation in the Medium and Dry treatments. As such, the possibility of using canopy temperature variability in irrigation management should be investigated.

Evapotranspiration.

It is commonly accepted that remotely sensed data has potential to be useful to farmers in making day-to-day management decisions. Satellite

data is of particular interest because it can cover large, inaccessible areas and can often circumvent lack of detailed ground data. However, there are still areas of research that must be addressed before an agricultural system utilizing aircraft- or satellite-based radiometer data can be designed.

The potential for use of remotely sensed data by farmers cannot be realized until the relationship between spectral data and crop and soil properties is fully understood. A detailed examination of what remotely sensed data can tell us about soil and crop conditions could allow use of such data for scheduling water, nutrient and fertilizer application and for making crop marketing decisions.

Spectral data from ground-based radiometers has been used successfully to assess the amount and the health of vegetation in agricultural fields. Models combining meteorological, agronomic and spectral data are available to detect the onset of plant stress and to assess plant properties such as phytomass and leaf area index. These models have, in turn, been useful as inputs to models of plant growth and evapotranspiration. However, much less investigation has been conducted to apply these models on a regional scale through the use of aircraft- and satellite-based radiometers. Some of the problems encountered in transferring ground-based technology to higher altitudes include radiometric and geometric scale differences and scanning/look angle.

Many of the models that will prove most useful to farmers on a regional scale (i.e., evapotranspiration estimation and irrigation scheduling) are based on scene radiation. The use of aircraft- or satellite-based spectral data with these models is inextricably dependent on atmospheric correction and sensor absolute radiometric calibration. These corrections are also necessary if the farmer wishes to compare data from the same area collected at several different times over a growing period.

Approach. The MAC experiment is a cooperative research project in which ground-based, low altitude aircraft and satellite spectral data are collected over an agricultural area every 16 days for a period of one year. MAC is an acronym for Maricopa Agricultural Center, a 2000 acre farm owned and operated by University of Arizona and located about 25 miles south of Phoenix. Since the farm is dedicated to research and development, large fields are monitored weekly to provide research projects with detailed crop growth data.

In general, data are being analyzed to ascertain the relationships between spectral data and crops and soil properties. More specifically, there are projects in progress to use remotely sensed data for estimation of 1) evapotranspiration, 2) soil moisture, 3) phytomass, 4) soil heat flux and 5) crop stress. Components of these projects include research on canopy architecture, soil and crop physics, atmospheric

characterization, instrument absolute radiometric calibration, and aerodynamic resistance.

Landsat Thematic Mapper spectral data of MAC farm is ordered for every unoccluded overpass. As each Landsat scene is received, a window of data is extracted and then geometrically corrected to correspond to the farm area. Data are displayed and assessed visually for any irregularities. Several fields are subsampled and the spectral data are regressed with plant parameters, such as crop cover, soil moisture and crop type.

The Remote Image Processing System (RIPS) is an integral part of the MAC experiment since the satellite spectral data are digital and require complex computer programs for processing. The RIPS consists of a microcomputer with a graphics board, a color video monitor and custom software for image enhancement and analysis. A tape drive was recently added to the system to allow magnetic tapes of Landsat data to be read directly into RIPS memory and to floppy disks.

Findings in 1985. Data collection for the MAC experiment will be complete in June 1986. Until recently, the majority of effort has been spent on data acquisition and processing and on preliminary data analysis. Data acquisition, processing and archiving for an experiment of this magnitude was a full-time project at the beginning of the experiment. Now the time spent on data collection is minimal and more time is available for concurrent analysis. Table 1 is a summary of data collection progress in 1985.

Evapotranspiration (ET) was evaluated by combining remotely sensed reflected solar radiation and surface temperatures with ground station meteorological data to calculate net radiation and sensible heat flux. Soil heat flux was estimated as a fraction of the net radiation, based on vegetation density. Instantaneous values of ET were calculated over cotton, wheat and bare soil and compared with ET values estimated using the Bowen ratio technique developed by Dr. Lloyd Gay (U of A). Preliminary results show good correlation between the two methods. Figures 1a and 1b are graphic representations of remote ET estimates using ground- and airplane-based radiometers compared to values obtained by the Bowen ratio technique.

To incorporate aircraft- and satellite-based spectral data in ground-based models, it is necessary to analyze the radiometric and geometric changes that occur as the instruments are raised to higher altitudes. An initial step in this analysis is to sample spectral data from similar radiometers at two altitudes (from aircraft and satellite) and compare the general trends of the data for sensitivity to actual ground reflectance characteristics. Figure 2 is an example of this analysis over a cotton field of partial, variable cover. High correlation coefficients were found between ground and satellite data in TM wavelengths for

visible, near-IR and mid-IR bands over several cover types, including partial canopy cover and bare soil. There was less correlation between trends in the thermal band, probably due to great differences in spatial resolution.

Interpretation. It is premature to address the preliminary results of the MAC experiment. Data collection procedures are operating smoothly and progress is being made toward understanding the type of dedicated system that may be necessary for agricultural use of high-altitude radiometer data. Most projects are finding that the airplane-based spectral data has good potential for use in existing crop and soil assessment models. The satellite data will be of greater use when the atmospheric correction and absolute calibration procedures are further refined.

Correlations between remote estimates of ET at two altitudes and Bowen ratio estimates of ET are good. In particular, the remote estimates of net radiation have been found to be quite reliable. Sources of error in the remote method have been identified and are being pursued to increase the accuracy of ET estimates. These sources include the estimate of aerodynamic resistance corrected for atmospheric stability and the soil heat flux estimate.

Future plans. We plan to continue collecting data every 16 days (weather permitting) until June 1986, refining collection methods as necessary. Upon completion, results will be analyzed and published. Research areas that we plan to address are:

1) Remotely sensed ET estimation;

2) Phytomass modeling;

3) An expert system for multi-database analysis;

4) Soil moisture assessment; and

5) Incorporation of aircraft- and satellite-based radiometer data in existing ground-based modes.

NEUTRON PROBE CALIBRATION

The use of neutron scattering probes for agricultural has made substantial progress in the past 30 years. Radioactive source strength and types of isotopes have changed significantly during this period, and electronic measuring and recording systems are now state-of-the-art. It is becoming simpler to use neutron probes to routinely measure soil water content and to be able to predict when crops need to be irrigated.

The major stumbling block in its use, however, is its calibration. Techniques for calibrating neutron probes have ranged from the use of different concentrations of neutron absorbers dissolved in water, to wet and dry sand or soil packed in containers, to in situ field measurements Each technique has its benefits and supporters, but there is no universally accepted method for calibration. Since soils may differ in their calibrations, then at a minimum, the soil of interest should be used in the calibration procedure.

Once a neutron probe has been calibrated for a particular soil, the question arises as to how that calibration can be transferred to another probe. This situation occurs when an individual or organization has several neutron probes in use and needs the probes to be interchanngeable. The purpose of this paper is to explore the use of plastic cylinders as standards to transfer the calibration from one neutron probe to another for other soil types.

Materials and Methods. Eight neutron probes representing two manufacturers were used to evaluate the transfer procedure using plastic standards. A description of these probes is given in Table 2. Four of the probes contained BF_3 detectors while the other four contained ^3He detectors, and one of the latter probes was of a different manufacturer than the others.

The technique we used was to record four 15- or 30-second counts (see Table 2) with the probe in its own housing, followed by four similar counts in each material of interest (plastic or soil). This way we were able to calculate a count rate ratio (counts in material/counts in housing) for each of the measurements. The count rate ratio was then related to the volumetric soil water content, and as discussed later, an equivalent water content of the plastic cylinders.

Plastic cylinders. A set of five high density (specific gravity = 0.941-0.965) polyethylene cylinders was used for the transfer standards. The cylinders were 60.0 cm tall and had diameters of 7.24, 8.72, 9.95, 11.55, and 12.40 cm. The inside was bored out to a diameter of 5.0 cm to accommodate the standard neutron probe without an access tube, and to a depth of 45.0 cm. This left 15.0 cm of solid plastic at the bottom to provide stability as the probes were being inserted and removed from the cylinders. We chose not to bore out the cylinders to accommodate access tube material, since we wanted a standard configuration and because tubing materials (aluminum, steel, and plastic) come in a variety of sizes.

After taking counts with the neutron probe in its housing, the probe was placed in one of the cylinders, the cylinder being about 1 m away from all other objects (operator, housing, and other cylinders). The probe rested on the bottom of the bore hole. We had some concern that the

position of the probe in the bore hole might influence the reading, but a simple test of taking counts with the probe elevated above the bottom in 2 cm increments to a height of 10 cm showed that the count rate was constant regardless of probe position. After taking four readings in each of the five cylinders, four additional readings were taken with the probe in its housing. The four readings in each of the cylinders were averaged and the eight readings in the housing were averaged so that a count rate ratio could be calculated for each cylinder for each neutron probe.

Soil calibration. One soil was used in the detailed calibration of the neutron probes: Avondale loam, a fine-loamy, mixed, calcareous, hyperthermic, Anthropic Torrifluvent. In this soil, three 2 x 2 m plots were established, and steel access tubes were installed in the center of each plot to a depth of 1.5 m. Each plot was irrigated with a different quantity of water at different times to establish different water regimes. About a week after the last irrigation, four readings with the neutron probe were taken every 20 cm to a depth of 120 cm. Of course, readings before and after each access tube were taken with the probe in its housing, so that count rate ratios could be calculated for each depth in each plot with each probe.

After the readings in the access tubes, soil core samples were taken to obtain volumetric water content. The core sampler, 7.5 cm inside diameter and 34.0 cm tall, was driven into the soil about 2 cm north on the access tube to a depth of 30 cm, and then dug out to obtain an intact core 30 cm long. A second core was taken on the south side of the access tube in the same manner. Each core was put into a container, weighed within a couple of minutes of removing it from the sampler, placed in an oven at 105°C to be dried for at least 24 hours, and then reweighed. Volumetric water content and bulk density were calculated for each core. The data from the two cores were averaged to yield one value of soil water content for that depth increment. Once the upper 30 cm layer had been sampled, the hole around the access tube was enlarged and excavated to a uniform depth of 30 cm from the soil surface. The next samples were taken by driving the core sampler to a depth of 20 cm (30-50 cm layer) both on the east and west sides of the access tube. After enlarging and excavating the hole to 50 cm, the process was repeated, alternating north-south and east-west sampling sites for succeeding depths. We felt that alternating the sampling sites would eliminate soil compaction problems caused by taking the samples one directly under another. Also, we assumed that the water content measured at the first 20 cm depth was representative of the 0-30 cm soil layer, and that each succeeding 20 cm reading would be assigned to a 20-cm layer (30-50 cm, 50-70 cm, etc.).

From the measured volumetric soil water content at each depth and the calculated count rate ratio at that depth, a calibration for each probe for each soil was obtained. Now, to evaluate how we could use the

plastic cylinders to transfer the calibration from one probe to another, one probe of each detector type was chosen as the standard: number 3960 was chosen for the BF_3 detector and 3898 for the ^3He detector. Using the direct soil calibration relationship for the soil and the count rate ratios obtained in the five plastic cylinders, an "equivalent volumetric soil water content" was assigned to each cylinder. The next step was to transfer the calibration to another probe by using the equivalent water content from the first probe and the count rate ratio from the second probe in each cylinder, and constructing a transfer calibration relationship. This way the slopes and intercepts of the direct soil calibration could be compared with the transfer calibration for each probe in each soil. The coefficients of determination (r^2) for the direct calibration of the eight probes were at least 0.95.

Results and discussion. The calibration coefficients (intercepts and slopes) for each of the probes for Avondale clay loam are given in Table 3. Our first thought was to use one probe as the standard for transferring calibrations regardless of detector type or manufacturer. However, we immediately found that the transfer procedure would only work between similar detectors. When a BF_3 detector was used as the standard to transfer the calibration to a ^3He detector, the transfer coefficients were larger for both the intercept and slope than the comparable direct soil calibration. Second, we found that the transfer procedure would only work for detectors of similar geometry. It became obvious very quickly that calibrations could be transferred between like detectors only. It is postulated that differences in detector behavior (energy levels measured by each detector), and detector geometry could account for the inability of transferring calibrations between unlike detectors. From Table 2, one notes that the comparison between direct soil calibration and the transfer calibration agree quite well where the detector type and manufacturer are the same.

To look at these results in a little different light, calculated volumetric water contents were compared to measured water contents using both the direct and transfer regression equations from each probe for each soil. These values are shown in Table 4, where one can see excellent agreement between the actual soil water contents and those derived from the transfer procedure for both the BF_3 and ^3He detectors. The lone exception is the Troxler probe which has a geometry different than the Campbell Pacific Nuclear (CPN) probes. Since we had access to seven CPN probes and only one Troxler probe, the results with the latter probe should be considered tentative until additional data is available.

Taking the calibration transfer procedure the next logical step, Table 5 gives the equivalent soil water contents for the five standard plastic cylinders for four soil types found in Arizona. The data are broken down into two types of detectors (BF_3 and ^3He) and two detector geometries or manufacturers (Campbell and Troxler). It is envisioned that

this table will be used by others who wish to calibrate their probes for one of the soils without actually going to the field. One would merely obtain a count rate ratio in each of the cylinders, and with the equivalent soil water contents, calculate the calibration coefficients. Since the relationship is quite linear, not all five cylinders are needed.

IRRIGATION SCHEDULING

Two methods of irrigation scheduling are currently in use at the USWCL. The first, a soil technique, is neutron measurements taken three times a week and used to determine the amount of water needed to refill the soil profile in each plot. Another method, a plant parameter measurement, is infrared thermometer (IRT) measurements taken daily and used in calculating a crop water stress index (CWSI) for every plot. A third method was introduced in the field for comparison with the other methods of irrigation scheduling. This method, another soil technique, uses gypsum resistance blocks installed beneath the soil surface to measure the resistance in the soil.

Methods and materials. Plots 2A and 4A were selected as sites for the installation of gypsum resistance blocks under a 1-1/2 year old alfalfa crop. Four blocks (Soilmoisture 5201) were buried 15 cm deep, halfway between the planks and south border, directly south of the access tube in both plots. The leads of the four blocks were connected to a data collection box located along the south border of each plot. These collection boxes (designed by John Cary of Kimberly, ID) automatically measure the resistance of each block once a day, storing the information in a 10-day capacity memory. After waiting the required 3-day initialization period, resistance, soil suction, and estimated days until irrigation for various soil factors were obtained from the data collection box using a HP-41CV hand held calculator which had been programmed to collect and calculate this data. These daily measurements were compared with the volumetric water content and fraction of extractable water left in the 0-30 cm layer, as calculated from the neutron measurements, and also compared with the CWSI calculated from the 1330 time-of-day infrared thermometer measurements. The estimated days until irrigation for each soil factor were evaluated in an effort to determine which soil factor was most closely related to the Avondale soil in which the blocks were located.

Results and discussion. Results from both plots were similar, but only data from 4A are discussed because a greater consistency was observed in this plot. Figure 3 shows crop water stress index, soil suction and fraction extractable water left in 0-30 cm layer as related to day of year. The relationship is agreeable among all three measurements except crop water stress index seems to be out of phase with the other two parameters. Soil suction measurements were very consistent with the fraction of extractable water until high levels of stress were encoun-

tered. At this point (day 306-312) suction measurements suddenly increased dramatically and 'Data Error' messages were continually displayed on the hand-held calculator while attempting to transmit the data. Measurements immediately dropped to their previous levels though upon application of water to the plot.

The relationship between soil suction and the fraction of extractable water left in the top 30 cm of soil is quite unique (Figure 4). The soil suction remains very low (<.5 bar) until 40% of the extractable water remains. While the next 10% of water is being removed, the soil suction increases another one-half bar. At that point (30% remaining), the soil suction increases dramatically. Following on from this observation, we investigated the relationship between the soil suction and the CWSI (Figure 5). Note the apparent lack of a unique relationship. This was not unexpected since, from Figure 3, we observed that the CWSI was generally out of phase with extractable water. This may be explained by the fact that the alfalfa roots are at least 2 m deep, as determined from soil water extraction patterns, which means that the water can run out in the top 30-cm layer and the plants still have enough water at deeper depths to maintain good crop growth under very little stress.

The calculator used to transmit soil suction data from the collection boxes was programmed to predict the number of days until soil suction reached values of 0.3, 0.5, 1, 3, 3.5, 5 and 10 under various soil factors. Soil factors used in these calculations included 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0. Evaluation of these data determined that estimaations from the 3.0 soil factor corresponded to the actual soil suction measurements better than the others. The estimated lengths of time were also found to be more accurate for time periods exceeding 10 days than for those of less time.

Conclusion. Measurements from gypsum blocks buried in soil followed the same pattern of changing soil conditions as fractions of extractable water values calculated from neutron measurements. On the other hand, no correlation could be found between CWSI and either of these soil measurements. If we had been investigating a shallower rooted crop, the results may have been quite different. Or, perhaps, if the resistance blocks had been buried at deeper depths, the relationship with the CWSI may have been better. Aside from the abnormally high readings under extremely stressed conditions, the soil moisture blocks performed very well and may prove a reliable method of irrigation scheduling in the future.

ALFALFA 84/85/86

Ground-based remote sensing investigations continued during 1985 in the field lysimeter plots located in the "backyard" of the U.S. Water

Conservation Laboratory. These plots were planted to alfalfa (Medicago sativa L. cv Lew) in February 1984. They were subjected to differential irrigation treatments beginning in late August 1984, which were continued during most of 1985. Stress treatments were rotated during this period so that experimental plots which experienced some stress during a particular harvest cycle would have two subsequent growth and harvest cycles to recover. Our experience in 1985 showed this was sufficient to permit recovery of plots which experienced very severe stress throughout one entire cycle. Carryover effects of antecedent stress were sometimes evident in regrowth behavior of the first harvest following one of the drier irrigation regimes, but no effects were noted in the biomass accumulation of subsequent harvests.

Treatments - 21 Aug 84 until 08 July 85.

The alfalfa stress experiment consisted of 2 replicates of 4 irrigation frequency treatments. The WET treatment experienced no appreciable water stress between cuttings (usually 2 irrigations). The EARLY treatment received one irrigation shortly after harvest, and often developed substantial stress levels prior to the next cutting. The LATE treatment received one irrigation midway into the regrowth period. Depending on antecedent soil moisture conditions, ambient evaporative demand and length of the period between harvests, the LATE treatments sometimes showed considerable symptoms of stress before the irrigation was applied. A DRY treatment received no supplemental water by irrigation from one harvest to the next. Expression of stress in this treatment also depended strongly on antecedent soil moisture conditions established prior to the treatment period. Usually the amount of water given during an irrigation was sufficient to replenish the extracted soil moisture to a minimum depth of 1.5 m. The amount of water applied to intended DRY and EARLY treatments was usually adjusted to refill the upper 0.9 m. This ensured that some stress would develop during regrowth. During the cooler months we observed that failure to observe this precaution would result in near-normal regrowth and little difference between these treatments and the WET irrigation treatment. The total amount of irrigation given at any one time did not usually exceed 15 cm in depth to minimize problems with scalding during the summer months. Plots which were not in the irrigation treatment rotation, were occasionally irrigated more than twice during a harvest period, so that soil moisture at deeper levels could be replenished.

Treatments - 08 July 85 continuing into 1986.

Harvest on 8 July 85 marked the end of the previous wet, early, late, and dry treatments. We embarked on an irrigation scheduling program based on the empirical method of calculating the Crop Water Stress Index (CWSI). Baseline coefficients for alfalfa were: intercept = 0.51°C and slope -1.92° C kPa^{-1}. The treatments were WET, LOW CWSI, MED CWSI and

HIGH CWSI. As before we established two replicate field plots per treatment level. All plots were irrigated shortly before harvest, then the WET plots were irrigated whenever the neutron probe measurements indicated that the plants had extracted 15 cm or more of the soil water below field capacity. The LOW CWSI treatment was irrigated whenever the 3-term daily running average of the CWSI exceeded 0.1 units. The MED CWSI was irrigated when the 3-term running average exceeded 0.2 and the HIGH CWSI when it was greater than 0.32.

Harvests. In 1985, we harvested the alfalfa plots 9 times (compared with 6 harvests in 1984, the first year of growth). Beginning with the November 1984 harvest, separate estimates of biomass were taken from the spectral reflectance target areas positioned on the south side of the boardwalks in each plot. These destructive samples were usually harvested the day before the rest of the field was cut. We used gasoline-powered hedge trimmers and cut a swath averaging 0.74 cm in width, about 8 to 10 m in length and parallel to the boardwalk. This area was divided into east and west target area segments which were measured with the Exotech radiometer, the Barnes Multiband Modular radiometer and the infrared thermometer. The alfalfa for the harvest biomass samples was cut at a relatively uniform average height of 4.2 cm (0.7 cm std dev) with the hedge trimmers. In the rest of the field a tractor-mounted cutter bar was used to mow the alfalfa leaving a more ragged stubble averaging 6.6 m (1.6 cm std dev) in height. The cut alfalfa was immediately transported to a tripod supported scale and its mass determined to the nearest 0.1 lb. Subsamples from each field sample were sealed in a plastic zip-lock bag, weighed to the nearest 0.1 g, dried in a convection oven at 70°C for a minimum of 72 hours and reweighed. The fraction of water contained in the subsample was used to estimate the total dry weight of the original field sample. Biomass (Megagrams ha^{-1}) was calculated by dividing the dry weight by the ground area subtended by the original sample.

Biomass from the lysimeters was estimated on the day the entire field was harvested using a curved blade linoleum knife. All the above-ground plant material was cut leaving a stubble height of about 2-3 cm. The entire sample was processed for dry weight. No effort was made to separate the sample into green and brown fractions of plant material.

Table 6 shows the results of biomass harvests of the target areas in each treatment during 1984-85. The highest yields obtained for the wet plots occurred during the summer when an average of 4.76 Mg ha^{-1} was recorded. The wet treatments yielded a cumulative 29 Mg ha^{-1} for 1985. With the exception of the February and March harvests the forage yields of the dry treatments showed considerable reduction below yields of the wetter treatments. Winter rains prevented the differential development of water stress from November 1984 until March 1985 and October 1985. Downy mildew disease and infestations of aphids and Egyptian alfalfa weevils were also a serious problem during this same period.

The irrigation scheduling treatment we designated the HIGH CWSI did not produce a reduction in yield despite the fact that these plots were stressed to a three-day running average CWSI of 0.32 units before irrigation. One reason for the apparent lack of response was the plots were usually irrigated immediately after harvest and thus started out each regrowth period with an ample supply of water. In August, the soil profile was essentially full, resulting in very little stress developing in the HIGH CWSI treatment before the September harvest. Regrowth in the following cycles, occurred during periods of lesser evaporative demand. The plants were able to extract sufficient water from the soil at these lower evaporative rates and maintain adequate production. A reduction in yield did begin to occur by the October and December harvests. This is an expression of the cumulative effects of deficit irrigation on that treatment.

Plant Biomass between Harvests. Estimates of plant biomass were obtained on a routine basis from August 84 until July 85. These provided a means to characterize the pattern of alfalfa growth as it was affected by stress imposed during the cycle. Samples were taken in the 8 field plots designated as treatment plots during any given harvest interval. The procedure involved cutting the alfalfa stems at an average height of about 3.75 cm above the soil surface with a curved-blade linoleum knife, immediately sealing the plants within a zip-lock plastic bag and transporting them to the laboratory for processing. Four circular 0.25 m^2 samples were taken from each of the field plots: 2 from the north half and 2 from the south. Even though the treatment plots were rotated so that maximum recovery was likely before they were again subjected to another water stress treatment, a special effort was made to insure that previously sampled areas were not resampled until at least 4 to 6 subsequent harvests had elapsed. Accordingly, sampling locations were positioned in opposing corners of each field and these locations were alternated each time a plot came into "treatment" status. The size of the ground area that was sampled was controlled by attaching a swivel-hook to the wooden handle of the knife such that it could be pivoted around a small metal stake positioned in the center of the sample. The "reach" of the knife was fixed so that when it was used in this fashion the cut area would be 0.25 m^{-2}.

A wet weight was obtained for the plants as soon as they were taken to the laboratory. Then they were stored in a refrigerator until processing could take place. Samples were separated into dry and green fractions and dried in an oven at 60-70°C for a minimum of 48 hours. Dry weights of each fraction were recorded and biomass (Mg ha^{-1}) calculated. Fractional water content was computed as (Wet weight - Dry weight)/Wet weight. Separate estimates of leaf and stem biomass were not made. Leaf area index was monitored during the June 85 regrowth period.

The sampling frequency was determined mainly by the rate of growth of the alfalfa. From August through 5 November 1984, plant samples were

taken 3 times a week. As the plants slowed in their growth, the sampling interval was adjusted to twice a week (until 6 December) and then once a week (until 1 April 85). The sampling frequency was then increased to 2-3 times weekly until 5 July 85.

Comparison of Biomass Estimates. Traditional biomass sampling operations are very labor intensive and time consuming. As a result the techniques we used were tailored to accommodate the size of the sample required. The gasoline-powered hedge trimmers proved very efficient for estimating the biomass of the remote sensing target areas prior to harvest, while hand trimming with a knife was safer and more effective within the lysimeters and also for the frequent, 0.25 m^2 samples which were obtained as often as 3 times a week. The two techniques left different amounts of stubble behind after the above ground portion of the plant was harvested. Our measurements indicated the hedge trimmers left about 4 m stubble after harvest, while hand harvesting with the knife left a stubble about 2-3 cm in height. Since the stems in the stubble are often rather woody and comprise a fairly heavy layer in the canopy, we expected the hand-cut samples to be much larger. However, the last hand-cut samples prior to harvest often occurred 3-4 days before the target areas were sampled, and had accrued less growth. Thus, in a comparison of the two techniques, differences in timing and cutting height were expected to be at least partially compensatory. However, the estimates obtained with the hedge trimmers in the target area averaged about 5 to 10% lower than the last daily hand-cut estimate prior to harvest (Figure 6). Much of this difference is probably due to cutting height alone since growth often slows before harvest as the plants sink proportionately more carbohydrates into root reserves.

Biomass samples also provided a means for comparing above-ground growth of plants confined within the weighing lysimeters (1 x 1 m surface area, 1.5 m rooting depth) with growth of plants in the surrounding field plots. Figure 7A shows that relationship for harvest cycles when the plants were not exposed to any water stress treatments. The lysimeter biomass estimates which were obtained by hand-cutting, show a fairly constant positive offset when compared with the field biomass estimates of the target areas. This bias is again due to the differences in sampling technique; plants cut by hand were larger than those harvested with the hedge trimmers. Although the variation in these data are considerable, it is not appreciably different from the variation shown in Figure 6. Because the slope of the trend line is close to 1.0, the growth patterns of plants in the reasonably well-watered lysimeters were similar to those growing in the surrounding field plots.

Figure 7B shows similar data for lysimeters and associated field plots which experienced some water stress during a harvest cycle. These represented only the EARLY irrigation treatments. DRY or LATE treatments were not imposed on the lysimeter plots since we felt that extreme

water stress for extended periods of time would be detrimental to alfalfa growing in a confined rooting zone. The variation in these data is considerable. In contrast to the unstressed conditions where (because of the cutting height advantage), biomass estimates within the lysimeter were slightly larger than those of the surrounding field, biomass from lysimeters in a stress treatment was usually lower than that found in the surrounding field. During cooler months and when natural rainfall prevented the development of significant stress in the EARLY irrigation treatment, the lysimeter biomass more closely approximated that of the surrounding field. Our conclusions are that the small lysimeters do not provide sufficient soil volume for a deeply-rooted perennial crop like alfalfa to be able to achieve growth patterns similar to the rest of the field when water stress conditions are imposed. However, when water is not limiting, growth within the lysimeters compare favorably with those observed in the rest of the larger field where rooting volume is not limited.

Leaf Area Index. Alfalfa leaf area was estimated for each of the irrigation treatment plots during the June-July harvest cycle in 1985 using an optically integrating leaf area meter (Licor Model 3100; 0.1 mm resolution lens in place). The plant materials used in this study were subsamples taken from two of the four, routine twice-weekly biomass samples collected from each treament plot during the same period. The ground area subtended by the biomass samples was fixed at 0.25 m^2, but the ground area subtended by the leaves used in the LAI subsample varied inversely with the biomass of the sample. Harvest reduced the canopy to stubble with very few leaves in the sample. A week later, however, regrowth had progressed to the point where the total number of leaves from a given 0.25 m^2 biomass sample was more than could be processed in a reasonable amount of time. Thus, a time limit of 10 minutes per sample was imposed on the processing procedure. All the leaves that could be run through the LAI meter during the 10-minute interval were used in the estimate of LAI. After measurement, the subsample leaves and stems were dried in an oven at 60-70°C for a minimum of 72 h. Dry weights were then measured and recorded. If the entire sample was not processed during the 10 minute time period, the ratio of dry weight of the processed leaves (plus their associated stems) to the total dry weight of the whole biomass sample was used to put the measured leaf area on a ground area basis for the calculation of leaf area index. Leaves were included in the estimate of LAI only if the leaflets had fully emerged from the bud. Experience revealed that the samples could be processed much more efficiently if they were not refrigerated prior to placing them on the conveyor belt of the meter.

Plant Canopy Temperature. A portable infrared thermometer (IRT, Everest Interscience, Model 110, nominal 4° field-of-view) was used routinely during 1985 to measure canopy temperatures of the alfalfa. Data collection began several days after harvest and continued until the following

harvest. Measurements were obtained on most workdays from 1330 to 1400 h MST. From April until August, canopy temperatures were also monitored during weekends to provide a continuous history of plant stress for irrigation management purposes. All plots were observed in both nadir and oblique directions. This provided us with data sets similar to those which might be acquired by airborne platforms or ground-based grower monitoring programs, respectively. In the irrigation treatment plots (8 plots per harvest cycle), the south half of each plot was viewed with the IRT pointed in each of the four cardinal directions and held at a declination angle of about 30° from the horizontal. Non-treatment plots were observed only in the east and west viewing directions. Nadir measurements were taken with the IRT pointed perpendicular to the canopy surface within the two reflectance target areas located to the south of the access boardwalks. Six separate measurements were made in each view direction. Concomittant measurements of dry and wet bulb temperatures at 1.5 m were obtained prior to IRT use with a hand-held, mechanically aspirated psychrometer (Bendix Model 566) and following the IRT readings with a stationary ceramic wick thermocouple psychrometer (1984 USWCL Annual Report) located in the "B" plots. Psychrometric observations preceding and following the canopy temperature measurements were averaged to give mean air temperature and vapor pressure deficits. Net radiation was obtained with miniature net radiometers (Fritschen MMR) positioned in the "B" plots. These micrometeorological parameters were used to calculate the CWSI on a daily basis.

Canopy Reflectance. Routine measurements of canopy reflectance were obtained using an Exotech Model 100-A radiometer configured with the Landsat MSS bandpass filters and 15° field-of-view apertures. Canopy reflectances were calculated by ratioing canopy radiances to incoming irradiances determined by frequent measurements of a horizontally positioned, painted $BaSO_4$ reference panel. Corrections were applied to the reference panel data to adjust for the non-Lambertian properties of its surface. Measurements of the $BaSO_4$ panel were made at the start, mid-point and finish of each sequence of field observations. A time-based linear interpolation was used to estimate irradiances at the time of measurement of each field plot. Data were collected at a daily time which corresponded to a nominal solar zenith angle of 57°, an angle which could be accommodated on a year-round basis. Measurements were obtained on most non-raining days. Ancillary observations included qualitative information on whether the solar disk was unobstructed or obscured by clouds to varying degrees, the type and extent of cloud cover, haze levels, wind speed and the relative amount of moisture on the plant surfaces.

Measurements were obtained over both the west and east target areas located to the south of the boardwalks in each plot. Six replicate "scans" of the four wavebands were taken in each target area with the radiometer held at arm's length above the canopy and positioned towards

the south. Data from the two targets were averaged to yield a mean reflectance for the plot. These target areas were identical to those viewed by the IRT and also were the same areas later harvested for yield information. Measurements were also taken over each of the lysimeters and a dry soil target of Avondale loam, the background soil for the alfalfa canopy. The entire measurement sequence took approximately 14 minutes to complete. At irregular intervals canopy reflectance measurements were obtained on a frequent basis throughout the day.

Anticipated use of this data set includes the development of a relationship between biomass and canopy reflectance, the testing of a model which predicts daily alfalfa canopy growth from a combination of canopy reflectance and emittance information, a evaluation of the effects of cloud cover on the reflectance of alfalfa and its use in predicting biomass, the characterization of regrowth patterns following harvest and the use of reflectance data as a surrogate for growth in evaluating the water use efficiency of alfalfa.

A Barnes Modular Multispectral 8-band Radiometer (MMR) was mounted on a backpack device to collect spectral reflectance data in the Thematic Mapper wavebands over the alfalfa plots on clear days only. Data were collected at a time corresponding to the approximate overpass of Landsat 5 (1030h). This resulted in 81 collection days from January through August. A particularly clear period occurred in June when spectral data were collected on all but five days in one growing period.

The MMR has waveband filters which mimic those of the visible, near-IR, mid-IR and thermal channels of the Thematic Mapper radiometer. It also has an additional near-IR channel which is proportedly sensitive to liquid water in plant tissues. An example of the response of the seven bands over a wet and a dry alfalfa plot is shown in Figure 8.

A portable micrometeorology station was deployed to record measurements of irradiance, windspeed, and dry- and wet-bulb temperatures at 6-second intervals. Estimates of evapotranspiration (ET) were calculated based on these meteorological data and ground reflectance. Figure 9 shows that the instantaneous remote sensing ET estimates correspond with hour-long averages measured using the lysimeters.

Soil Water Content. Volumetric soil moisture measurements were determined in the center of each of the 18 alfalfa plots and the 3 lysimeters on a 2 to 3 day interval using a Campbell Pacific Hydroprobe Model 503 (SN 2648). This probe consists of an Americium-241/Beryllium fast-neutron source and a Boron-10 trifluoride detector. The number of slow neutrons reflected back to the detector from the soil is directly proportional to the concentration of hydrogen (mainly in water) in a sphere of soil surrounding the probe. The neutron probe was calibrated for Avondale loam soil and the steel access tubes used in the alfalfa

experiment. Each access tube was positioned in the same location used in the previous several years of wheat experiments (SERIAL CEREAL 78-80, ANZA 82, CIMMYT 83). Soil moisture was determined for each 20 cm soil layer down to a maximum depth of 2.8 m. Fourteen of the alfalfa plots were monitored to that depth. Plots in the southeast portion of the field however, are underlain by a gravel layer which restricted the depth to which the access tubes could be installed. The access tube depth in Plot 3C is only 2.6 m; 4C is 2.2 m; 5C is 2.0 m; and 6C is 2.4 m. The lysimeters were measured to a maximum depth of 120 cm. Rubber stoppers prevented water from entering the tops of access tubes during irrigation. Occasionally water collected in the bottom of an access tube during an irrigation, in which case the affected depths were skipped.

Counting time was fixed at 30 seconds per depth. Daily variation in detector counting efficiency was compensated for by taking 5 standard reference counts (30 sec each) at the beginning and at the end of the field plot measurement sequence. These reference counts were taken with the entire unit positioned on a free-standing access tube about 1 m above the ground and the probe withdrawn into its protective housing. During the reference counts the operator stands well away from the probe to minimize any influence he may have on the counting rate. Previous experience in alfalfa had shown that when standard reference counts are taken in the field, the total counts were influenced by the proximity of the operator and changing conditions of the plant biomass surrounding the probe housing.

The measurement sequence usually required 3 hours to complete. To minimize damage to the plant canopy, soil moisture measurements were only done in the lysimeters when the plants were relatively small following harvest or just prior to an anticipated irrigation. Because the insertion of the probe changed the weight of the lysimeters, evapotranspiration estimates were also affected. This was kept to a minimum by measuring all the lysimeters within a single 30 minute averaging interval.

Data from the neutron access probe were processed to yield volumetric water content for each 20 cm level of soil. Upper and lower limits of volumetric soil moisture had been established during prior years experiments with wheat. Initially, these limits were used to set the upper and lower limits of extractable water for alfalfa. As our history of water contents for the alfalfa expands these limits will be adjusted to reflect the differences in rooting patterns and extraction of water for this deeply rooted perennial crop.

Plant Water Potential. Alfalfa water relations were characterized by water potential measurements obtained using the Scholander pressure bomb technique. These measurements were taken 2 or 3 times each week between

February and July 1985. Measurements were obtained between 1300 and 1430 h, a time period which coincided with the daily IRT observations. Bomb measurements were usually only acquired from the 8 plots designated as treatment plots (4 treatments X 2 replicates) during a particular harvest cycle. Our field procedure involved taking three separate plant samples per plot, each from a different site located 2-3 meters in from the north berm. Sampling was rotated so that the 3 replicate measurements per plot were representative of an average time period over the 1 to 1.5 h period instead of being clustered together in time. Each stem was individually cut with a razor blade, immediately placed in a light proof, moistened cloth bag to minimize tissue water loss, transported to the pressure chamber and sealed within an elongated chamber. Pressure was applied slowly until the xylem fluids could just be seen exuding from the cut end of the stem. Then the pressure at that time was recorded. Stems were only cut once in the field and water relations were usually determined less than a minute later.

Short stubble and slow regrowth precluded pressure bomb measurements immediately after harvest. Usually measurements could be obtained after the plants attained a height of 15-20 cm. At times the plant stems were soft and succulent. This caused problems when the chamber was pressurized and the plant stem wall collapsed before reaching a suitable end point. Uneven rates of soil water depletion were particularly evident in the southmost plots of the backyard field (i.e., the "C" plots). This was most noticeable during the spring and summer of 1985 when those plots were subjected to a water stress treatment. The common pattern was that the south half of these plots would run out of water first, becoming very stressed and with a significant reduction in growth when compared with the north half. The dividing line was coincident with the east-west access boardwalk. Unfortunately, the IRT canopy temperature measurements were always taken from the south half, where destructive plant sampling procedures were kept to a minimum. Pressure bomb measurements were taken from the north portion of the field until the problem became very evident, then they were switched to the south half. The result was that some of the pressure bomb measurements did not correspond well with the IRT data taken. Future analysis and experiment designs will have to keep this in mind.

Leaf Diffusion Resistance. Measurements of stomatal resistance characteristics were observed in the treatment plots using a LiCor Model LI-1600 stead state porometer and a Polycorder data logger from January until June 1985. Readings were taken from 1300 to 1400h twice weekly from January until mid-April 1985. At that time the frequency was increased to 3 times weekly. Three upper and three lower leaf surfaces were observed for plants in each treatment plot. Two replicate plots were included per treatment. Combined leaf resistances and conductances were calculated by considering the upper and lower surfaces to be operating as parallel resistances.

Plant Photographs. A permanent visual record of the condition of the alfalfa field plots was provided by weekly photographs. Color slide film (Kodachrome 64) was used in a 35 mm camera equipped with a 55 mm focal length lens. Several panoramic views of the entire field were taken from the top of the lysimeter lab building. Then nadir viewing photographs were taken from a height of about 4 feet in the center of each of the two target areas in each field plot (a total of 36 photographs). Alignment of photographs in the same place each week was made possible red marks on the east-west access planks which traverse each plot. A single oblique photograph was taken in each plot from the south irrigation berm looking towards the north. Nadir viewing photographs were taken of each lysimeter. After processing at a commercial laboratory, the slides are labeled and archived for anticipated analysis of percentage plant cover, relative stand vigor and color, lodging information and percent bloom.

Plant Pests. During 1985, the insect pest population in the alfalfa experiment grew quite large and, at times caused considerable damage to our alfalfa. To assess the effect of the insect population, we regularly took sweep samples in the alfalfa, and identified and counted the insects. Samples were taken only from the treatment plots so we could determine if the irrigation treatments had any effect on the insect populations.

Early January, before we started with the samples, the alfalfa was sprayed with insecticide to control a large infestation of aphids. Five days later most of the aphids were dead and so were almost all of the predators. Because of the detrimental effect on the predators, the next time aphid infestation was controlled by releasing ladybird beetle adults, Hippodamia convergens, purchased from an insect supply house.

Ten sweeps were taken from each treatment plot each sample time. Samples were taken from the north end of each plot on one day and from the south end the next day. Since samples were never taken more than twice a week, one end of the field was never sampled more than once a week. The area that the sweep samples were taken from was about one meter into the plot and ran the entire width of the plot. The depth that the sweep net penetrated into the alfalfa was about 4 to 8 inches, so only the top one-half to one-third of the alfalfa was being sampled. Once the samples were taken from a plot they were placed into one pint ice cream cartons and put into a freezer for approximately one-half to one hour. This would kill most of the insects and slow the rest of them down long enough so they could be counted.

After starting the sweep samples we had one infestation of blue alfalfa aphids and one of Egyptian alfalfa weevils. From the information obtained from the sweep samples we were able to determine that we had a problem early enough to do something about it. Ladybird beetles were

released on the 13th and 15th of March and the aphid population started decreasing almost immediately (Table 7). Since there were no control plots where there were no ladybird beetles, we could not determine if they were entirely responsible for the decrease in the aphid population, but one has to expect that they had a major impact on the pests. There was no significant difference (at the 95% confidence level) in the average number of insects between the treatment plots.

EFFECTS OF PARTIAL CANOPY COVER ON THE CWSI

The CWSI derived from radiant canopy temperatures and ambient micro-meteorogical conditions is a very useful parameter for quantifying water stress. Its sensitivity to plant stress is enhanced by conditions of moderate to high evaporative demand--prerequisites for maximum temperature differences between well-watered and non-transpiring canopies. The CWSI's effectiveness is diminished however, when used for less than complete canopy cover because varying proportions of soil are viewed by the infrared radiometer. The consequence of viewing the soil, which is usually warmer than the plants, is that it inflates the CWSI to levels which are much higher than independent observations of plant water status would actually indicate.

This problem becomes especially acute when soil surfaces are dry and have been exposed to high intensity insolation. The problem is less serious following an irrigation or rainfall which wets and cools the background soil temperature or when the surface of the soil is shaded by relatively tall, sparse vegetation. It can be minimized by viewing the canopy at an oblique angle to reduce the influence of the background soil temperature on the composite temperature viewed by the IRT. Interpretation of aircraft or satellite data is complicated by the nadir view which increases the amount of viewed soil. Successful use of the CWSI during the stand establishment of agricultural crops will require a more comprehensive understanding of this problem. For perennial forage crops such as alfalfa which are harvested as often as every 4 weeks during the summer months, it is a problem which must be addressed during the regrowth period following every cutting.

Theoretically the CWSI should vary between zero and unity over the range of water stress conditions experienced in the field. A CWSI close to zero is typical for a vigorous canopy that is growing at an optimum rate and which, by virtue of a recent irrigation, is judged to have optimum water status. At the other extreme, a CWSI of 1.0 indicates a canopy which has ceased transpiration in response to severe water stress conditions. Figure 10 shows CWSI data collected in the backyard alfalfa experiment during a harvest cycle in July and early August 1985. Four field plots were chosen which differed in their antecedent moisture history and thus could be expected to exhibit varying rates of regrowth. The timing of the initial post harvest irrigation of these plots was

also allowed to vary to provide a range of background soil surface temperatures on any given day. The CWSI was calculated according to the empirical methodology of Idso et al. (1981), using oblique canopy temperatures obtained with the infrared thermometer held at an angle of about 30° from the horizontal. Immediately apparent from an inspection of Figure 10, is that the CWSI is much greater than the expected upper limit of 1.0 for the first 10 days after harvest. Considerable scatter is also evident in this figure. This is mostly a function of the different regrowth rates induced by antecedent stress and timing of the first post harvest irrigation. The latter was also responsible for differences in background soil temperature. Adding to the scatter was the fact that all days were used in the calculation of the CWSI, including some when the cloud cover might have affected the surface temperatures.

The CWSI does not behave as expected and yield values near zero when the plants are known to be in near-optimum water status, until almost two weeks following harvest. The reason is simple: the plants have to attain a certain minimum size before the IRT measures apparent canopy temperatures which are not influenced either directly or indirectly by the thermal energy of the background soil. The length of this interval during which the CWSI is not useful for monitoring stress would be expected to shrink or expand depending on water application, ambient temperatures, solar radiation, etc. It is not expected to become much shorter than 12-14 days but could easily last a month or more in cooler climates. Similar problems exist during the establishment of most annual crops. For example, the partial canopy problem exists for a 2-3 month period following a late November planting of spring wheat in central Arizona.

A plant growth parameter like the vegetation index discussed in the next section and shown in Figure 12 is more germaine to describing the problem than the number of days after harvest. In fact, if one looks more closely at Figure 10 and examines the data for each field separately (not shown), the data for the faster regrowing plots fall to the left of the trend line while the fields which were slower in regrowth fall to its right. Using the NIR/Red ratio to characterize regrowth would give each plot a common denominator and might allow the same fundamental relationship to be applied to different locations and crops.

Graphing the CWSI versus the vegetation index (Figure 11) does reduce most of the scatter seen in the previous figure and permits an empirical solution to the partial canopy problem. The large amount of scatter seen in the CWSI when the vegetation index is between 2 and 4 is predominately a function of differences in moisture of the surface soils. Plots which were irrigated exhibit CWSI values between 1.0 and 2.0 with the non-irrigated plots showing higher values. The relationship between the CWSI and the vegetation index is fairly well defined because the data are independent of its rate of plot regrowth. Once the vegetation

index reaches a value greater than 10 or 11 the CWSI begins to behave as expected for a non-stressed canopy. This point corresponds to 100% canopy cover when the plants are viewed from the same oblique angle used with the IRT.

The most encouraging aspect of the relationship portrayed in Figure 11 is that it offers the possibility of correcting the CWSI to remove the effect of background soil temperatures or of developing a new index which combines remotely sensed canopy reflectances and temperatures into a single number which describes plant growth.

MONITORING ALFALFA BIOMASS VIA SPECTRAL REFLECTANCE MEASUREMENTS

Conventional estimates of above ground plant biomass require intensive destructive sampling of vegetation on a routine basis. For a rigorous analysis of alfalfa growth, the size and number of samples needed to minimize sampling errors are large. Because the plants grow so quickly, the frequency with which samples should be taken is often greater than can be accommodated with limited field size, labor, and oven drying space. The ability to characterize biomass accumulation using non-invasive, remote sensing techniques would avoid many of these problems and provide researchers with a useful new tool for growth analysis.

The physical basis for remote assessment of plant biomass arises from the bidirectional spectral reflectance properties of plant canopies and those of the underlying soil. Healthy green plant foliage has a very low reflectance in the visible portion of the spectrum. Reflectance in the red region is particularly low (2 to 4%) because it is light in these wavelengths which is trapped and used in the photosynthetic pathways. By contrast, light in the near-infrared portion of the spectrum is reflected very strongly by vigorous vegetation. The reflectance characteristics of most agricultural soils are quite different from those of plants and are dependent on the surface water content. Reflectance of visible light from the soil may be up to an order of magnitude greater than for green plants, while that in the near-IR might be half that of the plants.

Vegetation indices are generic terms used to refer to multiband combinations of target reflectances that tend to maximize the differences in spectral information between plant canopies and background soils. They can take the form of simple band ratios, normalized differences between bands or linearized combination of bands which have been optimized to yield specific information about a particular target of interest. The simple ratio of NIR/Red reflectances and a normalized difference between these bands [(NIR-Red)/(NIR+Red)] are common examples of vegetation indices useful for biomass assessment. They are particularly sensitive to green biomass, relatively insensitive to changes in wetness of the soil background and have the distinct advan-

tage of retaining much of their information content even under conditions of varying illumination intensity and cloud cover. This feature makes these ratio type indices superior to many of the other vegetation indices which are additive combinations of the reflectances in several different bandwidths.

The ongoing alfalfa experiment at the U.S. Water Conservation Laboratory backyard lysimeter field plots provided an opportunity to establish the relationship between alfalfa biomass and various vegetation indices calculated from the spectral reflectances measured routinely with ground-based portable radiometers. A secondary objective was to examine the effect of variable sky conditions and cloud cover on that relation.

Radiometric Observations. Crop canopy reflectances were measured using an Exotech Model 100A portable radiometer equipped with 15° field-of-view optics and spectral bandpass filters similar to those of the Landsat Multispectral Scanner:

Exotech	Landsat	Region	Wavelength
Band 1	MSS4	Green	0.5-0.6 μm
Band 2	MSS5	Red	0.6-0.7 μm
Band 3	MSS6	NIR	0.7-0.8 μm
Band 4	MSS7	NIR	0.8-1.1 μm

The radiometer was handheld at arm's length over pre-designated target areas measuring approximately 1 by 9 m. Access to these targets was provided by east-west boardwalks which were elevated about 20 cm above the surface of the soil in each field plot. All measurements were taken with the radiometer extended towards the south and viewing the plants in a nadir fashion. Each lens of the radiometer viewed an area approximately 30 cm in diameter when the plants were 50 cm in height.

Observations were made daily from 01 April until 04 June 85 at a time period corresponding to a constant solar zenith angle of 57°. Data were collected regardless of sky or cloud conditions. Analog signals from the radiometer were recorded on Polycorder portable data loggers which also recorded the time when measurements were taken. Reflectances were calculated as the ratio of radiances measured over each alfalfa target to irradiances inferred from a time-based linear interpolation of data collected at 6-8 minute intervals over a 0.6 by 0.6 m, horizontally positioned painted $BaSO_4$ reference panel. Correction factors were applied to the $BaSO_4$ data to compensate for the non-lambertian reflectance properties of the panel at a solar zenith of 57°. Twelve measurements were made in each alfalfa plot. These were combined to yield an average reflectance for each plot.

Biomass Sampling. Above ground plant biomass was estimated from 4 -

$0.25\ m^2$ circular destructive samples taken at 3 to 4 day intervals over two harvest cycles during the Spring in 1985. Plants were cut in in the field using a sharpened, curved-blade linoleum knife leaving a stubble height of about 2.0 to 3.0 cm. Wet weights were obtained in the laboratory and green and brown plant fractions were separated and dried for at least 48 h at 60-70°C. Dry biomass was calculated as the average dry weight per $0.25\ m^2$ sample multiplied by four ($g\ m^{-2}$).

Observed levels of biomass increased regularly with time between harvests. If water was not limiting, regrowth was usually very rapid following harvest then slowed as the canopy matured and the time of next cutting approached. When plants were stressed for moisture, the biomass sampling technique was sensitive enough to reveal a leveling off and in some cases a decrease in above ground biomass levels. Behavior of the observed data was consistent with the treatments imposed on the experimental fields and did not reveal large unexpected fluctuations which are often seen in this type of data. Since the reflectance data and biomass were sampled on a different time scale, it was desirable to have biomass data for every day that reflectances were measured. This was achieved by applying a second degree sliding polynomial curve fitting procedure to the twice weekly biomass data.

Relationship between Biomass and Spectral Reflectance. The sensitivity of a vegetation index, in this case the simple ratio of reflectances in the Near-IR to those in the Red wavelengths is shown in Figure 12. This figure shows interpolated daily values of total dry biomass versus the index measured on those days when the direct beam solar irradiance was unobstructed by clouds. These data were collected from one replicate of all 4 irrigation treatments and two harvest cycles during the Spring. A conspicuous feature of these data is the inflection point when the value of the index is approximately 12. This corresponds to a point in time when biomass is about 125-150 $g\ m^2$ and canopy closure approaches 100%. We have chosen to describe this relationship by two linear relations which intersect at this 100% canopy cover point.

Prior to complete canopy cover the ratio index shows high sensitivity to increasing amounts of vegetation, with relatively little scatter around the trend line. A relatively small increment of growth elicits a large increase in the vegetation index. Our daily data during this early regrowth period reveal growth from day to day very clearly. In several short term studies the effect of antecedent moisture stress was evident in the initial regrowth patterns of plots irrigated at the same time. In cases where morning and afternoon measurements were conducted during the same day, it was even possible to see changes in the ratio index during that period which were associated with very short term increases in biomass.

After the developing canopy completely covers the soil, however, the slope of the relation between the index and biomass increases dramati-

cally. A larger change in biomass is required to evoke a unit increase in the vegetation index. Note also, that the amount of scatter in the data increases markedly and the variation appears to rise proportionately with increasing biomass. A suggested reason for increased variablity is that the index is very sensitive to subtle changes in canopy architecture. As the plants increase in biomass there is a corresponding increase in height making the canopies more susceptible to day-to-day rearrangement by wind. It is also possible that the index is responding more to changes in apparent LAI than total biomass and, if stress alters the ratio between LAI and biomass (lower leaf drop was evident in the EARLY and DRY treatments) then this will introduce additional variability. Alfalfa flowering also begins at higher biomass levels. Its intensity is dependent on moisture stress and may have affected the quality of reflected light measured with the radiometer.

Effect of Cloud Cover on Biomass Estimates. Reports in the literature have indicated that ratio type indices are relatively insensitive to changing illumination intensities because both bands tend to behave in a similar fashion when direct beam solar irradiance is reduced. In as much as spectral reflectance measurements were collected as often as possible during the spring and careful qualitative observations of sky conditions were also made, it was possible to sort the data according to the cloud conditions which might have affected their quality. This provided an excellent opportunity to test the hypothesis that reflectances and derived vegetation indices could be used to predict biomass even under conditions which have traditionally been considered unsuitable for making quality remote sensing measurements.

Figure 13 portrays the same information on the NIR/Red index and total biomass shown earlier but data for days when the sun was obscured by varying degrees of cloud cover (open square symbols) are superimposed on the unobscured sun data points (solid square symbols) and the regression lines derived from them. The variation exhibited by the data points for cloudy conditions appear to be scattered randomly above and below the trend lines and no greater in amplitude than the "clear" data. This is particularly encouraging because it implies that ground-based remote sensing techniques can be used to predict biomass under extreme cases of changing irradiance.

Single band canopy radiance or reflectance data are well correlated with total biomass levels under conditions when illumination conditions are fairly constant and the sun is unobstructed (solid square symbols in Figures 14A and B). However, cloud cover interference with the direct beam of the sun introduces considerable scatter into the relationship (open square symbols) and precludes their use under all but optimum conditions. The variability in these single bands when there is cloud cover explains why linear combinations of the bands also are inadequate for predicting biomass under less than optimum illumination conditions.

Figure 15, for example shows that the performance of a 2-space greenness index derived from the Red and Near-IR reflectances is also seriously degraded by clouds. Judicious selection of the type of vegetation index used to infer biomass levels has an important bearing on the results when variable cloud conditions have occurred during data collection. Ratio type indices appear superior to linear combinations of bands under these conditions.

MEASURING CANOPY GEOMETRY IN ALFALFA

Remote sensing techniques have potential for detecting and quantifying the degree and areal extent of crop stress. In particular, the reflected solar and thermal infrared (IR) portions of the electromagnetic spectrum have been used to infer crop condition. Measured canopy spectra is complicated by the changes in both leaf physiology and canopy geometry as the leaves dehydrate. Further complications ensue when you consider a heliotropic crop, such as alfalfa, where diurnal spectral measurements are influenced by leaf motion that may be relatively independent of stress level.

Solar tracking, or heliotropism, is the phenomenon of sun-following by leaves. Solar tracking within the alfalfa canopy is interrupted midday by leaflet cupping. The cupping response is typified by an elevation of leaflets converging on the central axis. The midday cupping response observed in alfalfa leaves is reportedly a response to water stress.

Solar tracking measurements were collected in stressed and unstressed alfalfa fields. Two sunlit leaves were selected from eight plants per field and three parameters were measured from sunrise to sunset: leaf spread, leaflet zenith and leaflet azimuth. Leaf spread is the distance between tips of opposite leaflets at rest. Leaflet zenith is the angle between the leaflet surface and a vertical axis as measured with a hanging protractor. Leaflet azimuth is the compass direction of a line perpendicular to and originating at the middle leaflet surface. Exact time was recorded as each leaf was measured and the solar azimuth and zenith were calculated to correspond with leaflet orientation. At end of day, the total leaf spread was measured by expanding opposite leaflets to full extension.

Two indices of canopy architecture were calculated from these measurements: cosine of incidence and cuppedness. The cosine of incidence is a measure of integrated incident solar radiation interception by the leaflet surface, calculated as follows:

$$\text{cos incidence} = \cos(\text{leaf azimuth} - \text{solar azimuth}) * \cos(\text{leaf zenith} - \text{solar zenith})$$

where the cosine of the differences between leaf and solar angles indicates the fraction of the maximum possible incident solar radiation that

the leaflet intercepts due to either its azimuthal or elevational orientation.

The cuppedness index is simply the leaf spread at rest standardized by the total possible leaf spread:

cuppedness = leaf spread at rest/total leaf spread.

Diurnal measurements were made on two days, in late spring and in early fall. A third collection will be conducted in mid-winter for seasonal analysis. On measurement days, the architecture data was collected (as described) in addition to diurnal spectral readings, plant water potential and plant biomass.

The relationship between cupping and tracking is influenced by sun angle and follows trends found by previous research on similar crops. Both the well-watered (wet) and stressed (dry) field canopies start the day with a strong tendency toward heliotropism and little or no cupping. Tracking degrades toward solar noon as cupping increases. Cupping decreases about 2 hours after solar noon and tracking activity is restored. Diurnal hysteresis is evident in both the cosine of incidence and the cuppedness index; tracking ability in the afternoon is not restored to the high level achieved in the morning at corresponding sun angles.

Several differences in the response in the wet and dry fields should be noted. The dry field canopies begin cupping sooner and to a greater degree than the wet field canopies. Also, the dry canopies show greater hysteresis in cuppedness and cosine of incidence than the wet, even though it is not uncommon for both fields to have similar canopy indices in the morning measurements.

Corresponding spectral reflectance measurements show similar trends of diurnal hysteresis. Hysteresis is greater for the dry than the wet plots and there is some confusion at solar noon. However, unlike the cuppedness index and the cosine of incidence, wet and dry canopies do not tend to start the day with similar reflectances in each waveband. The initial reflectances appear dominated by the density of green biomass present in the field.

Smaller data sets of architecture measurements were collected on two winter dates (Jan. 17 and Jan. 25, '85). These sets do not show the trends obvious in the late spring and early fall samples, discussed above. Cupping differences at solar noon are much less pronounced, perhaps not significant at all. The cosine of incidence is consistently moderate and does not vary significantly over the day. Also, early morning and late evening tracking ability appears equal in magnitude.

Results show that the alfalfa canopy is heliotropic and experiences cupping to varying degrees depending on season and stress level. Furthermore, well-watered plants exhibit different canopy geometry trends than those of drought stressed plants. Comparisons of canopy geometry indices with spectral reflectance observations show that both exhibit patterns which vary with solar zenith angle and diurnal hysteresis which is greatest for plants under higher levels of water stress.

Unfortunately, the leaf water potential also follows these trends and thus, we have not isolated the relative effects of plant physiology and canopy geometry on spectral reflectance. However, there is one trend that deserves further research. It appears that the canopy geometry of dry and wet fields is relatively identical at low sun angles in the morning. The spectral response, on the other hand, is significantly different between the fields at that time of day. Further data collection is necessary to strengthen this hypothesis.

Several hypotheses have arisen from a small but intensive sample of alfalfa canopy geometry:

1) Geometry differs significantly in winter and summer;
2) Geometry is affected by plant stress; and
3) Geometry effects can be isolated from effects of changes in plant physiology at low sun angles in the morning.

These hypotheses will be expanded and tested by collection of a larger data set with more replications for each condition, e.g., winter, summer, stressed, unstressed, morning, afternoon.

PERSONNEL

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Table 1. MAC farm data collection summary for 1985.
Key: F = field number
C = cover type:
W = wheat/barley
C = cotton
A = alfalfa
S = bare soil
P = plate

Q = quality of data:
1 = excellent
2 = good
3 = poor

		GROUND						AIRCRAFT		SATELLITE	
DAY OF YEAR, 1985	WEATHER	MMR F C Q	EXOT/IRT F C Q	OBLIQUE IRT F C Q	PHOTOS Q	CR21 F C Q	AUTOMET F C Q	EXOT/IRT Q	PHOTOS Q	Ordered or Received	Atmospheric Data Q
108	clear	31 W 1		22 A 1	1	21 A 2				R	1
124	light cirrus around sun	30 C 1 31 W 1			1		31 W 2			R	2
140	clear	28 C 1			1		28 C 1				
156	clear, cirrus along horizon	29 C 1 30 C 1			1		29 C 1				1
172	clear	30 C 1			1		30 C 1	1	1		2
188	light cirrus around sun	29 C 1 30 C 1	22 A 1 21 A 1	22 A 1	1		29 C 1	1	1		3
204	clear, scattered cumulua	28 C 1 29 C 1	22 A 1 21 A 1	22 A 1	1	21 A 1	29 C 1	1	1	R	1
220	clear, cirrus along horizon	31 C 1 32 S 1			1	21 A 1	31 C 1	1	1		2
236	clear, cirrus around sun	31 S 1	22 A 3 21 A 3	22 A 1	1	21 A 3	28 C 1	1	1		3
268	cirrus over sun	21 A 1	22 A 1 21 A 1	22 A 1	1	21 A 1	28 C 1	2	1		
284	clear, cumulus on horizon	13 S 1 22 A 1	22 A 1 21 A 1	22 A 3	1	21 A 1	28 C 1	2	1		1
300	clear, cumulus & cirrus around sun	21 A 1	22 A 1 21 A 1	22 A 1	1	21 A 1	13 S 1	1	2	R	1
348	clear	13 S 1	22 A 1 21 A 1	22 A 1	1	21 A 2	21 A 1	1	1		1
364	cirrus and cumulus over aun	21 P 1	22 A 1 21 A 1	22 A 1	1	21 A 1	21 A 1	1	1		

Table 2. Neutron probes used in field calibrations.

Probe Manufacturer	Model	Probe I.D.	Detector Type	Source Strength (mCi)	Count Time (sec)
Campbell	503	2648	BF_3	50	30
Campbell	503	3070	BF_3	50	30
Campbell	503	3383	BF_3	50	30
Campbell	503	3960	BF_3	50	30
Campbell	503	3898	^3He	50	30
Campbell	503	4498	^3He	50	15
Campbell	503	5882	^3He	50	30
Troxler	3332	137	^3He	10	30

Table 3. Calibration coefficients for two types of neutron probe detectors in Avondale clay loam.

BF_3 Detector

Probe No.	CPN 3960	CPN 2648		CPN 3070		CPN 3383	
Calibration	Direct	Direct	Transfer	Direct	Transfer	Direct	Transfer
Intercept	-0.110	-0.098	-0.090	-0.096	-0.090	-0.086	-0.081
Slope	0.394	0.427	0.409	0.383	0.367	0.374	0.368

^3He Detector

Probe No.	CPN 3898	CPN 44900		CPN 5882		TROX 137	
Calibration	Direct	Direct	Transfer	Direct	Transfer	Direct	Transfer
Intercept	-0.104	-0.108	-0.108	-0.108	-0.104	-0.036	-0.087
Slope	0.322	0.315	0.313	0.277	0.277	0.630	0.496

Table 4. Measured and calculated volumetric water contents in Avondale clay loam.

Sample No.	Measured Θ_v	Calculated Θ_v — BF_3 Detectors: 3960 Direct	2648 Direct	2648 Transfer	3070 Direct	3070 Transfer	3383 Direct	3383 Transfer
1	.129	.142	.145	.143	.141	.138	.145	.147
2	.202	.199	.191	.187	.197	.191	.195	.196
3	.208	.204	.208	.202	.209	.202	.207	.207
4	.215	.215	.218	.212	.213	.207	.215	.215
5	.216	.214	.215	.210	.218	.211	.214	.214
6	.246	.256	.256	.249	.258	.249	.256	.255
*7	.278	.241	.235	.229	.241	.233	.238	.237
8	.210	.213	.209	.204	.209	.203	.210	.210
9	.223	.222	.224	.218	.223	.216	.228	.228
10	.231	.234	.229	.223	.230	.223	.227	.227
11	.306	.316	.315	.306	.312	.301	.313	.312
12	.304	.293	.296	.287	.298	.288	.298	.297
13	.276	.281	.282	.273	.282	.272	.282	.281
14	.273	.275	.276	.267	.277	.268	.278	.277
15	.256	.229	.229	.223	.229	.221	.228	.227

Sample No.	Θ_v	^3He Detectors: 3898 Direct	4498 Direct	4498 Transfer	5882 Direct	5882 Transfer	137 Direct	137 Transfer
1	.129	.137	.138	.136	.143	.147	.141	.053
2	.202	.198	.196	.193	.197	.202	.205	.103
3	.208	.207	.205	.203	.209	.213	.211	.108
4	.215	.215	.214	.212	.215	.219	.211	.108
5	.216	.214	.214	.211	.214	.218	.215	.111
6	.246	.253	.253	.250	.255	.260	.248	.137
*7	.278	.238	.235	.232	.239	.243	.248	.137
8	.210	.212	.211	.209	.209	.214	.213	.109
9	.223	.225	.227	.224	.227	.231	.226	.120
10	.231	.229	.229	.226	.227	.231	.235	.126
11	.306	.314	.312	.309	.314	.318	.318	.192
12	.304	.293	.294	.291	.294	.298	.298	.177
13	.276	.284	.283	.280	.284	.288	.281	.163
14	.273	.277	.278	.275	.279	.283	.273	.157
15	.256	.235	.238	.236	.229	.233	.222	.117

*Data were not used in calculating slope and intercept values because of compaction of soil sample (bulk density = 1.79 g/cm^3).

Table 5. Equivalent volumetric soil water contents for five plastic cylinders from four soils, two detector types and two detector geometries.

Cylinder No.	1	2	3	4	5
			BF_3 Detector (CPN)		
Soil Type					
Avondale	.0158	.1974	.3956	.6417	.7425
Mohall	-.0011	.1560	.3244	.5367	.6213
Superstition	.0285	.1522	.2876	.4555	.5243
Cibola	.0902	.2404	.4048	.6086	.6921
			^3He Detector (CPN)		
Soil Type					
Avondale	-.0267	.1195	.2851	.4926	.5831
Mohall	-.0357	.0939	.2362	.4216	.5025
Superstition	.0120	.1028	.2085	.3417	.3722
Cibola	.0557	.1756	.3153	.4914	.5652
			^3He Detector (Troxler)		
Avondale	.0633	.2188	.4247	.7050	.8303

Table 6. Results of target area alfalfa biomass samples taken in 1984 and 1985.

Average Yields (Mg ha^{-1} dry weight)				
	Irrigation Treatment			
DATE	WET	EARLY	LATE	DRY
14 Nov 84	2.51	2.22	2.46	1.81
06 Feb 85	2.65	2.64	2.59	2.60
26 Mar 85	2.36	2.24	2.21	2.08
03 May 85	3.85	2.95	4.36	2.51
04 Jun 85	4.45	3.29	3.74	2.12
05 Jul 85	4.76	3.96	4.03	3.01
		LOW CWSI	MED CWSI	HIGH CWSI
05 Aug 85	3.60	3.42	3.44	3.24
09 Sep 85	3.32	2.99	3.12	3.04
15 Oct 85	2.21	2.47	2.57	2.11
16 Dec 85	1.77	1.78	1.70	1.03

Table 7a. Numbers of Insects/Sweep Irrigation Treatment (1985)

	WET						DRY					
	05 Mar	08 Mar	12 Mar	14 Mar	19 Mar	26 Mar	05 Mar	08 Mar	12 Mar	14 Mar	19 Mar	26 Mar
PESTS												
Egp. alf. weevils	0.4	0.5	3.7	4.95	3.25	0.15	0.65	0.5	3.2	7.3	5.7	0.45
Aphids	150.0	276.60	643.5	347.7	267.6	280.8	170.0	243.6	739.2	498.9	368.7	367.2
3-corn. alf. hoppers	—	0.1	—	0.05	—	—	—	0.1	—	—	—	—
Lygus	—	—	—	—	—	0.25	—	—	—	—	—	0.45
PREDATORS												
Ladybugs	—	—	—	0.05	0.1	—	—	—	—	—	0.1	—
Lacewings	—	0.1	0.05	0.05	—	0.2	0.05	—	—	0.1	—	0.30
Parasit. wasps	3.0	1.25	2.90	0.95	1.9	1.95	3.0	1.05	1.40	0.65	2.15	2.45
Big-eyed bugs	—	—	0.05	—	—	—	—	—	—	0.05	—	—
Pirate bugs	—	—	—	0.05	—	0.2	—	—	0.1	—	—	0.25
Spiders	0.15	0.2	0.20	0.1	0.1	0.1	—	0.05	0.25	0.15	0.15	0.05
Redavids	—	—	—	—	—	0.05	—	—	—	—	—	—
Nabids	—	0.05	—	—	—	0.1	—	—	—	—	—	—
Syrphids	—	—	—	—	—	0.05	—	—	0.1	—	—	0.3
Collops	—	—	—	—	—	—	—	—	—	0.05	—	—

Table 7b. Number of Aphids/Sweep Irrigation Treatment (1985)

Date	Wet	Early	Late	Dry	$\overline{X}$
05 Mar	300	260	240	340	285.00
08 Mar	553	600	411	487	512.75
12 Mar	1287	999	1311	1478	1268.75
14 Mar	695	977	959	998	907.25
19 Mar	535	442	566	737	1507.00
26 Mar	561	606	755	374	574.00
$\overline{X}$	655.166	647.333	707.000	735.666	686.291

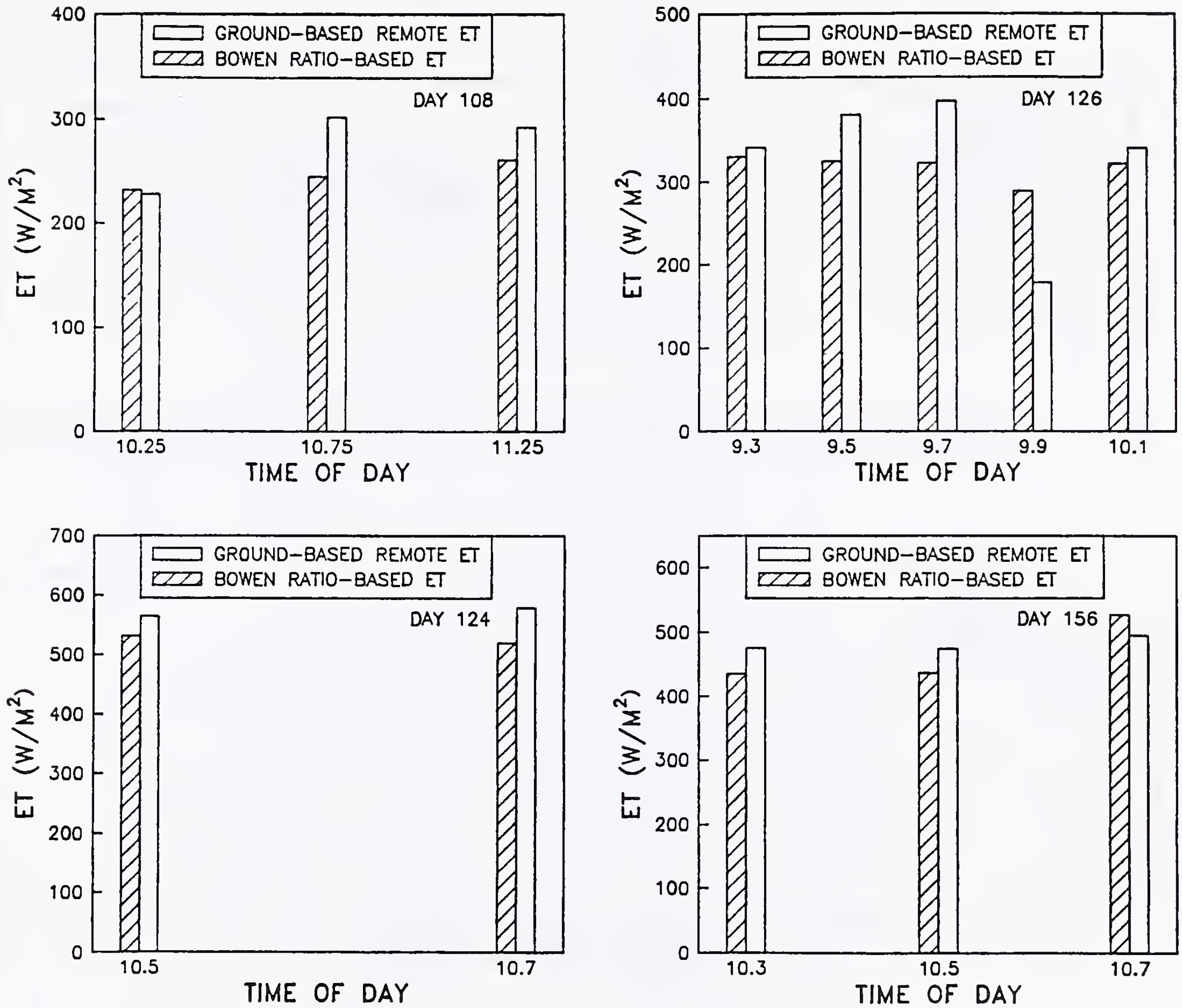


Figure 1a. Ground-based remote ET estimates over a cotton field at MAC farm compared with Bowen ratio-based ET.

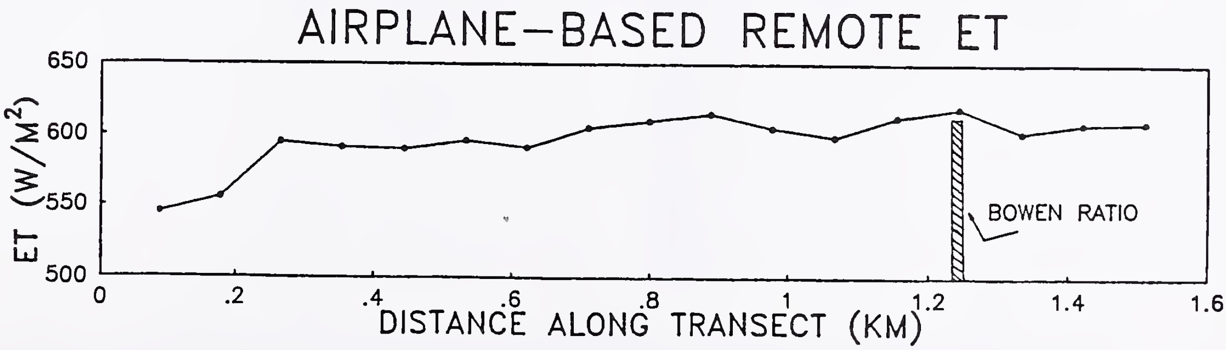


Figure 1b. Airplane-based remote ET estimates over a cotton field at MAC farm compared with Bowen ratio-based ET.

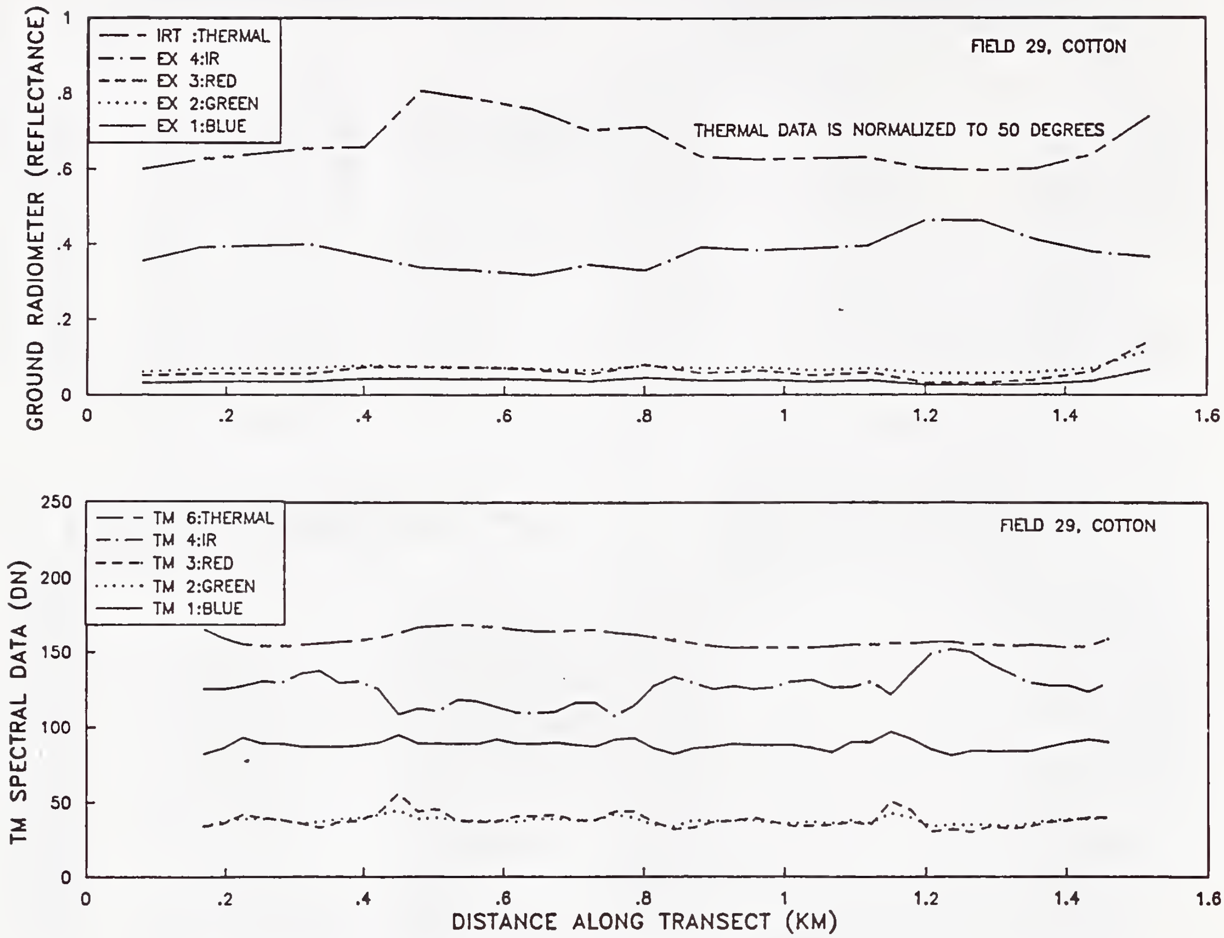


Figure 2. Comparison of Thematic Mapper satellite data and Exotech ground spectral data over cotton on 23 July 1985.

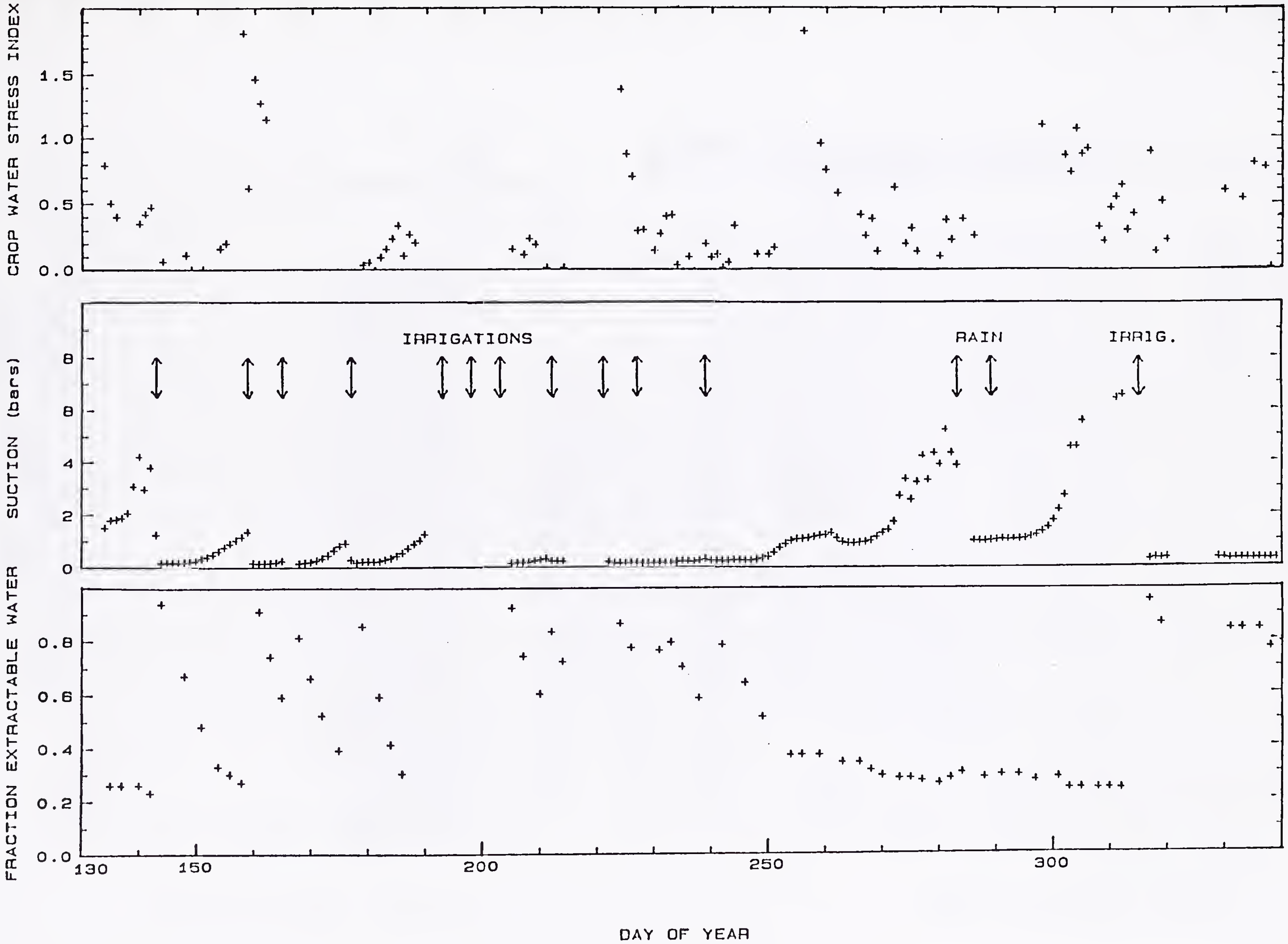


Figure 3. Fraction extractable water, soil suction and crop water stress index with respect to day of year.

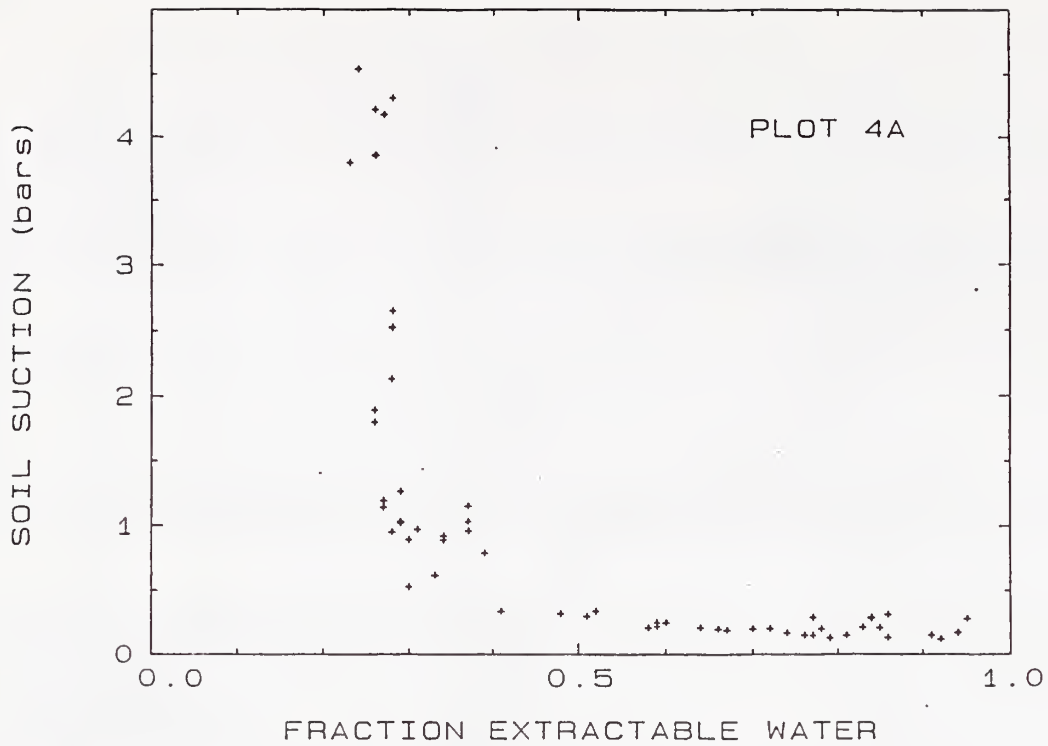


Figure 4. Fraction extractable water remaining in 0-30 cm soil layer versus soil suction.

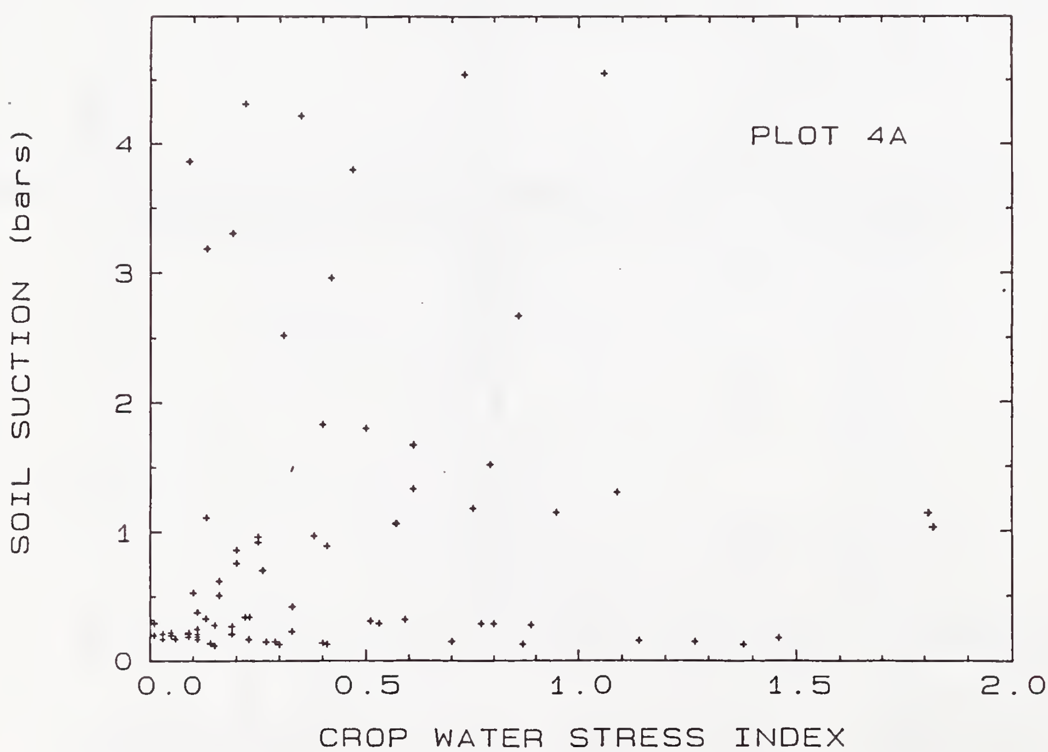


Figure 5. Crop water stress index as a function of soil suction.

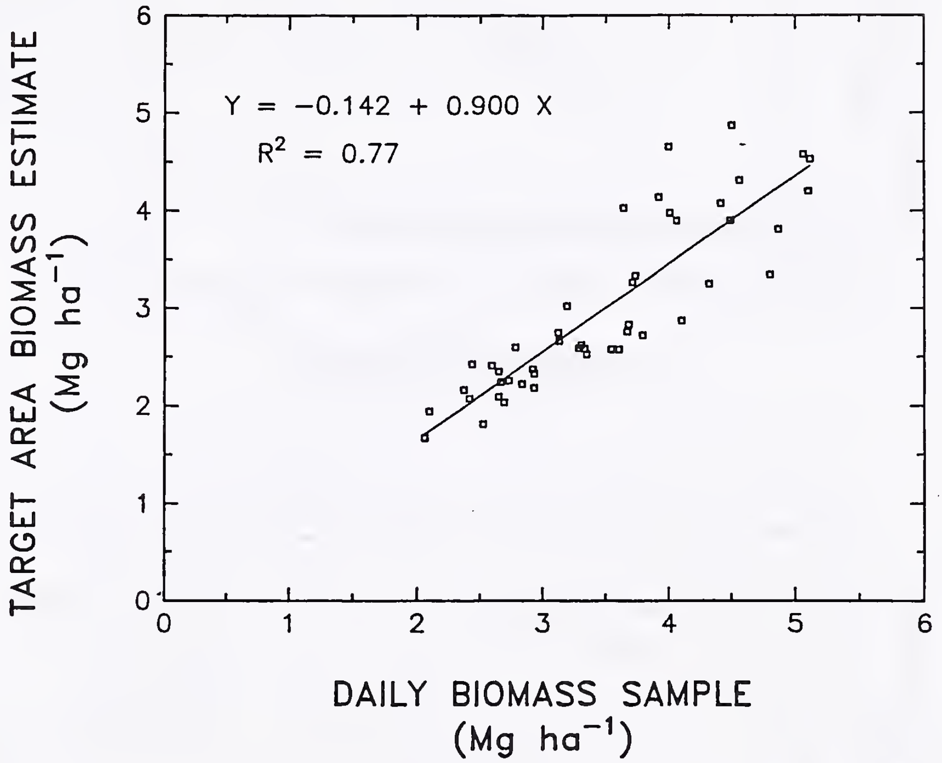


Figure 6. A comparison of two biomass sampling techniques used in the alfalfa experiment. Target area biomass estimates were obtained with hedge trimmers just prior to cutting the rest of the field. Daily biomass samples were actually the average of the last 0.25 m^2 samples taken prior to harvest.

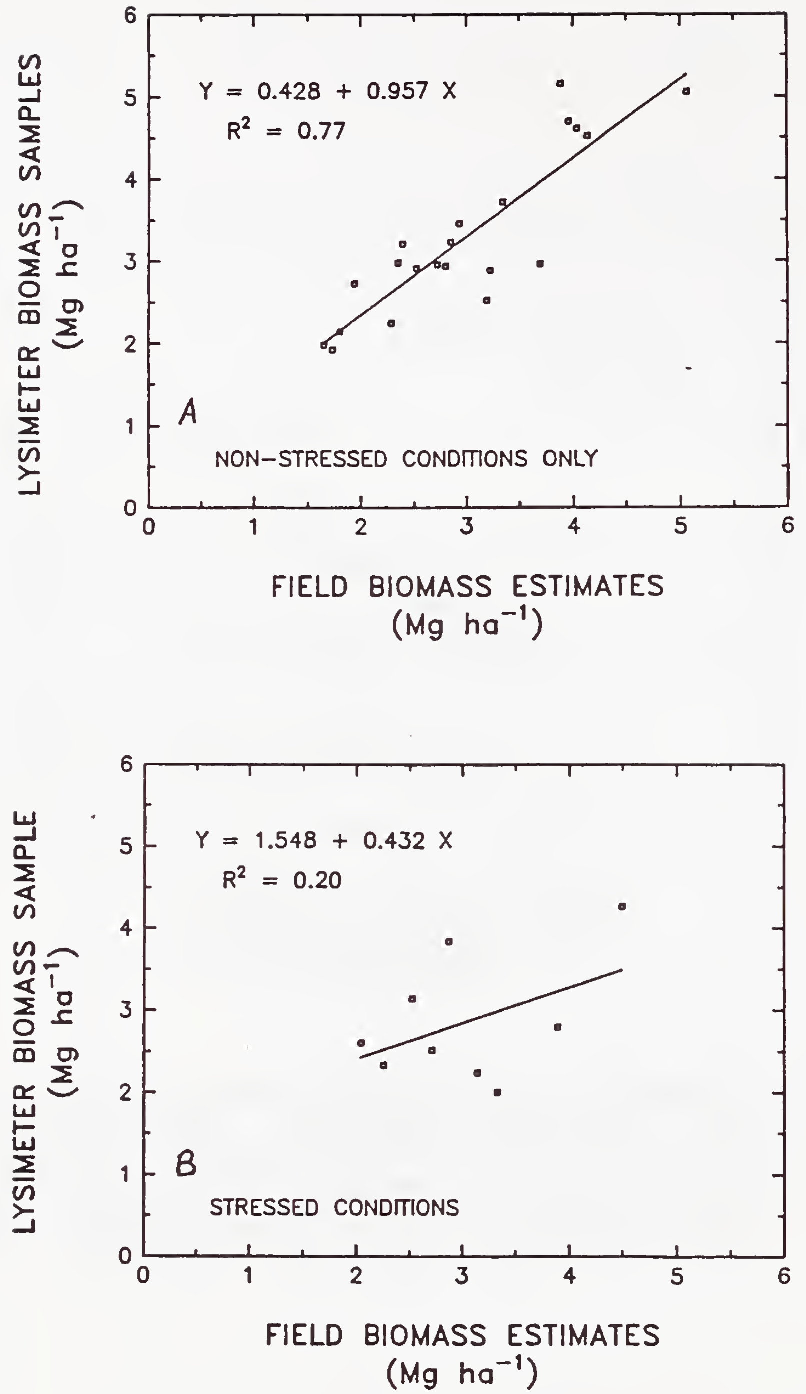
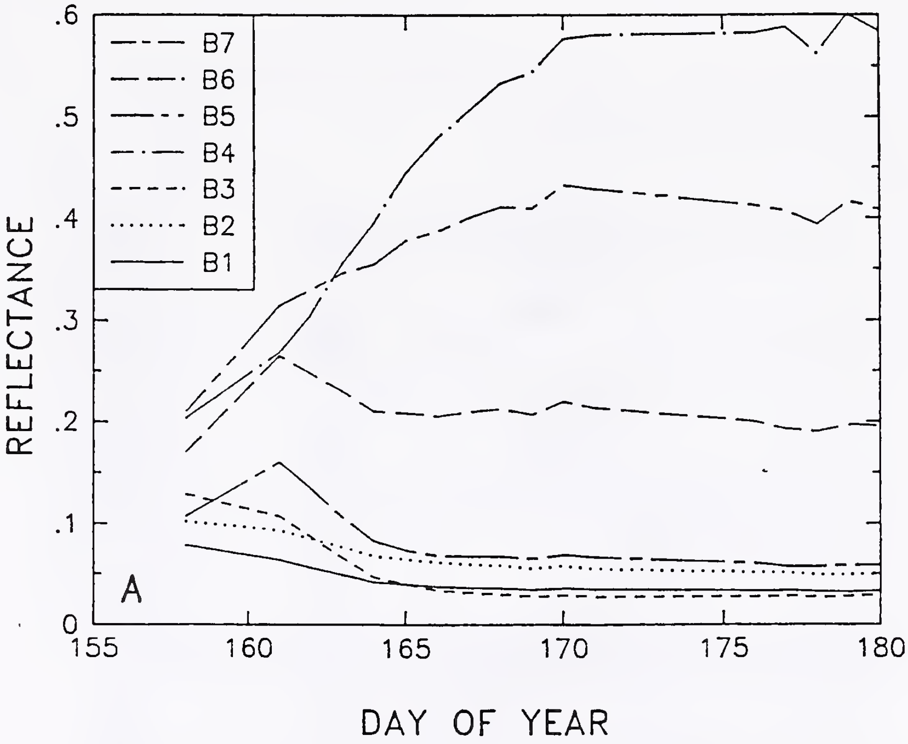


Figure 7. Comparison of biomass samples from the lysimeters with estimates obtained from the target areas of the surrounding field during harvest cycles when alfalfa was not subjected to water stress (7A) and when alfalfa was in a water stress treatment (7B).



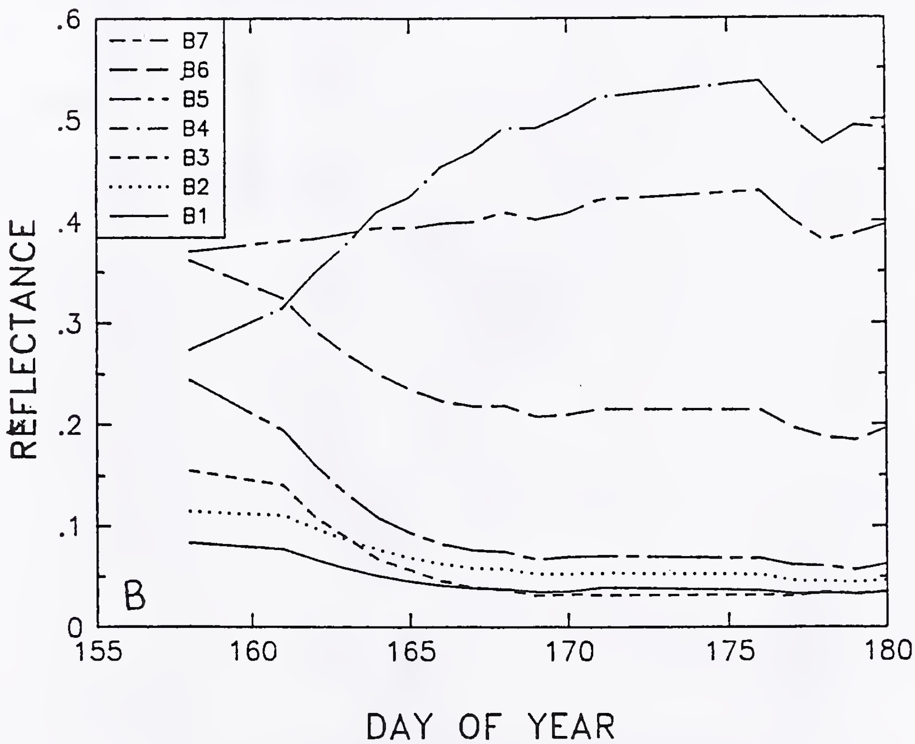


Figure 8. Spectral reflectance over well-watered (A) and stressed (B) alfalfa plots in the MMR wavebands. (B1, 0.45-0.52; B2, 0.52-0.60; B3, 0.63-0.69; B4, 0.76-0.90; B5, 1.15-1.30; B6, 1.55-1.75; B7, 2.08-2.35 μm).

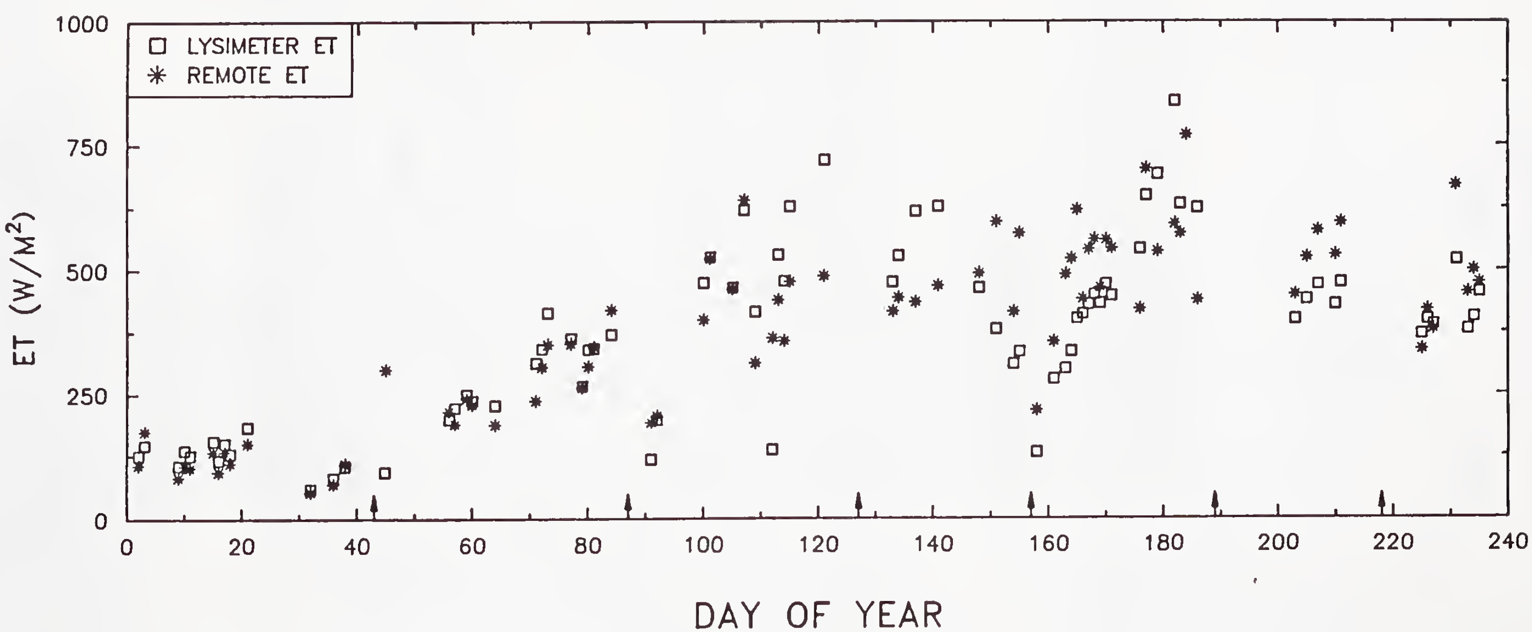


Figure 9. Comparison of remote- versus lysimeter-based estimates of evapotranspiration for several growing periods. Arrows along the X-axis indicate harvest dates.

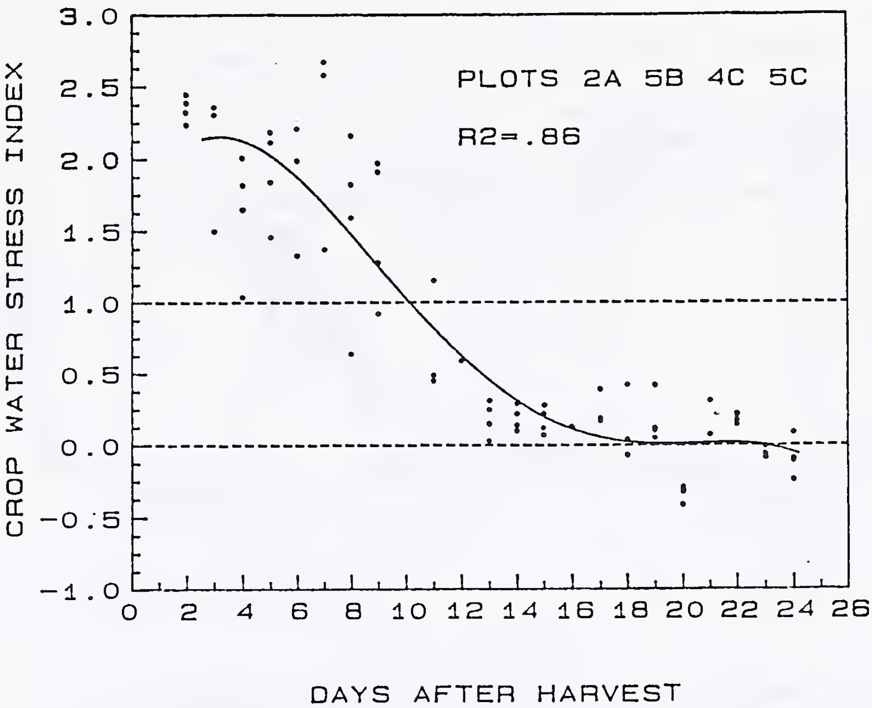


Figure 10. Crop water stress index values for alfalfa following harvest in July 85.

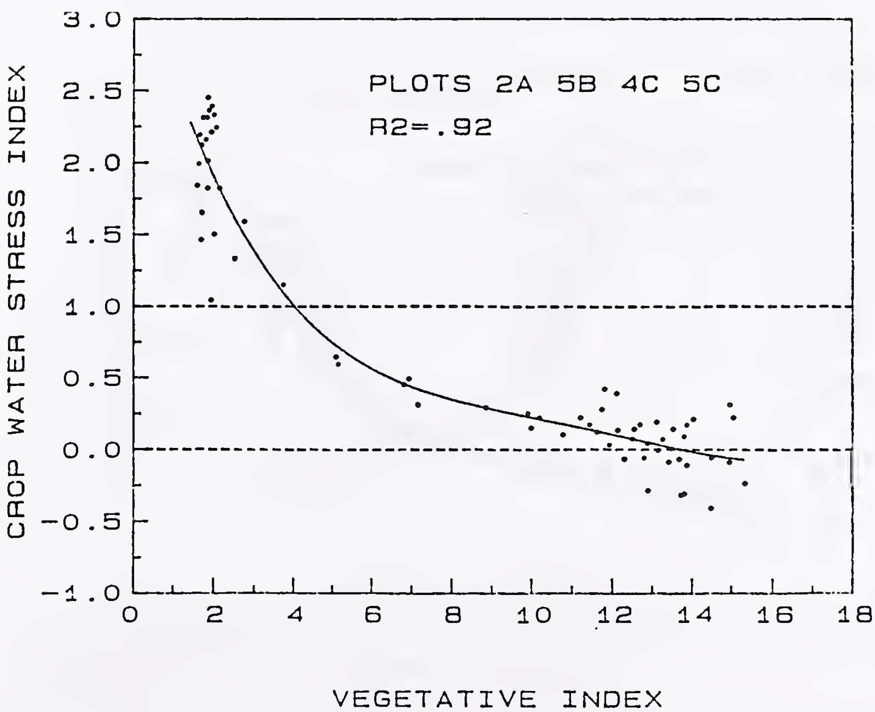


Figure 11. The crop water stress index shown as a function of the vegetative index (ratio NIR to Red reflectance) measured following harvest in July 85.

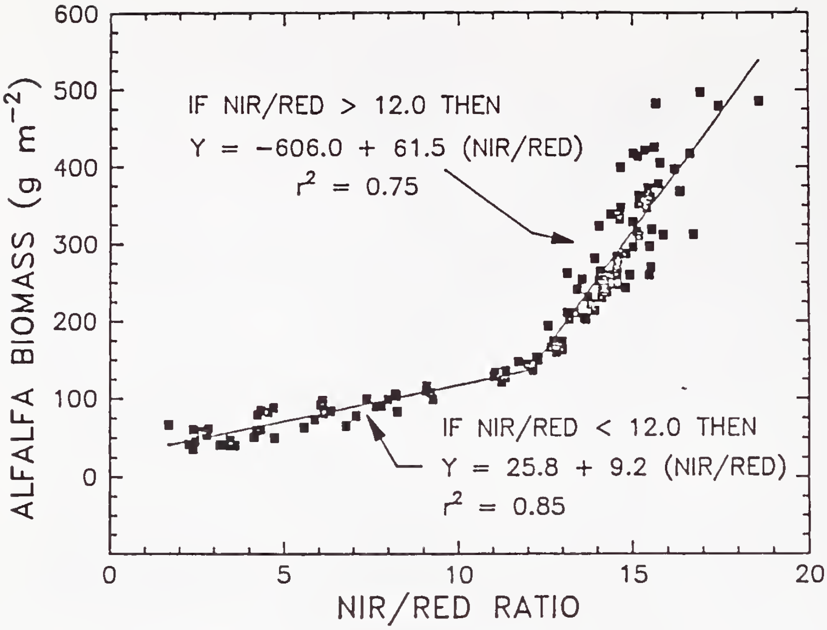


Figure 12. Daily values of alfalfa biomass versus the ratio of NIR to Red reflectances measured using the Exotech radiometer on days when the solar disk was not obstructed by clouds.

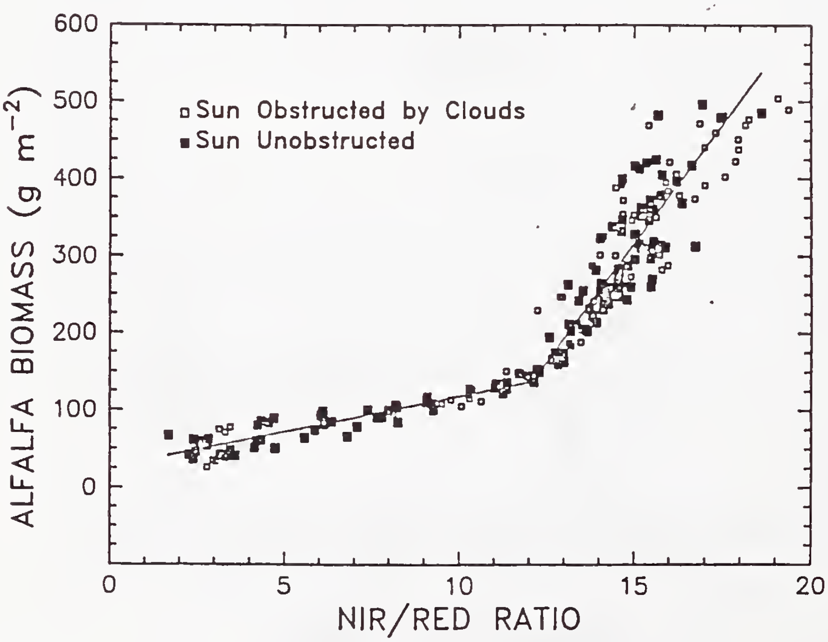
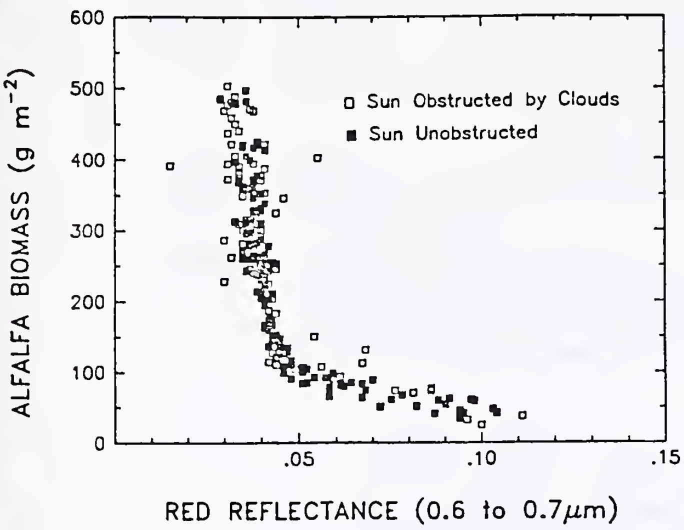


Figure 13. Daily values of alfalfa biomass versus the ratio of NIR to Red reflectances measured with the Exotech radiometer. Days when clouds interfered with the solar disk are shown superimposed on the trend line for cloud-free data.



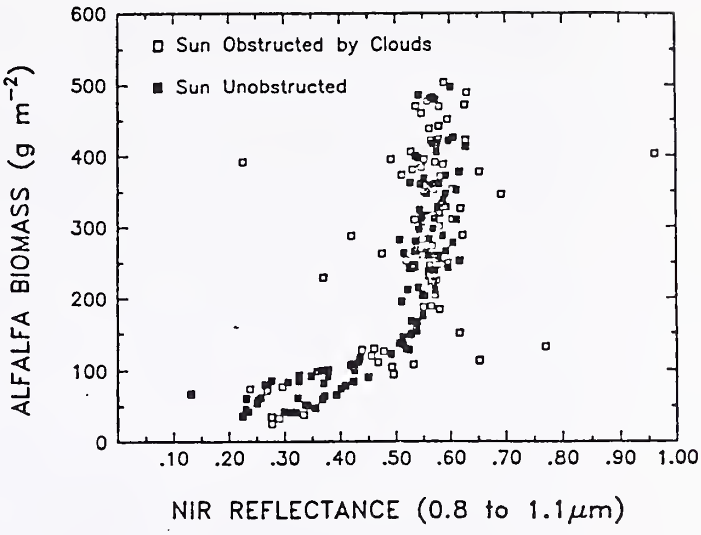


Figure 14. Daily alfalfa biomass versus single band reflectances measured with the Exotech radiometer.

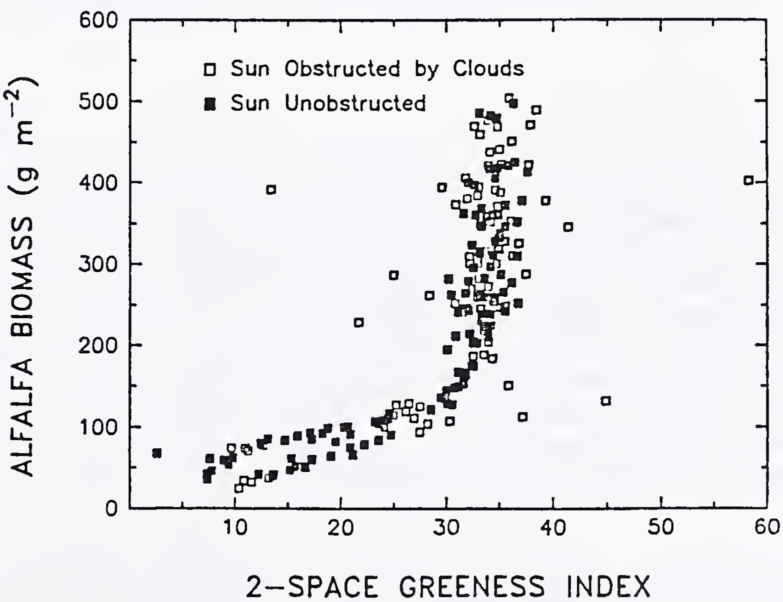


Figure 15. Daily alfalfa biomass versus a spectral greenness index measured with the Exotech radiometer. (Greenness = $-0.761 * \text{Red} + 0.649 * \text{NIR}$).

TITLE: EFFECTS OF INCREASING ATMOSPHERIC CO2 ON YIELD AND WATER USE OF CROPS

NRP: 20760 CRIS WORK UNIT: 5510-20760-006

OUTLINE

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MATERIALS AND METHODS
- A. Culture of Experimental Crop
- B. Irrigation and Water Use
- C. Carbon Dioxide Concentrations

RESULTS
- A. Leaf Area, Biomass, and Yield
- B. Flower Production and Boll Retention
- C. Photosynthesis at Chamber CO_2 concentrations
- D. Photosynthetic Responses to Changes in CO_2 Concentration
- E. Diurnal Variation of Carbohydrates
- F. Stomatal Resistance
- G. Leaf Temperatures
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SUMMARY AND CONCLUSIONS

PERSONNEL

INTRODUCTION

This was the third year of a project whose main objective is to determine the long term effects of continuous CO_2 enrichment on the yield, water use, and photosynthesis of a variety of plants under optimal and limiting levels of water and fertility. The purpose is to document the possible effects of the future doubling of global atmospheric CO_2 concentrations on crop production. Secondary objectives are to determine the effects of increased CO_2 on physiological determinants of crop productivity, on water stress and stomatal behavior, and on biochemical reactions that limit photosynthesis. Staff members from the U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory are cooperating on the project.

Like 1983 and 1984 (Kimball et al., 1983, 1984), the 1985 experiment was conducted on field-grown cotton (*Gossypium hirsutum* L.) using open-top CO_2-enrichment chambers. The CO_2 treatments were ambient, 500, and 650

$\mu\ell\ \ell^{-1}$ in the chambers, as well as open-field control plots. There were two replicates of each treatment. The 1985 experiment included well-watered and water-stress irrigation level treatments, similar to 1984. A major improvement in 1985, however, was a switch from flood to drip irrigation, thereby achieving much more precise control of the water application. In other respects, the 1985 experiment sought to replicate the 1984 experiment and the well-watered treatment of 1983.

MATERIALS AND METHODS

A. Culture of the Experimental Crop

The cotton crop was grown on the field just west of the Western Cotton Research Laboratory, Phoenix, Arizona, on the same plots as the 1984 experiment (Kimball et al., 1984). A plot plan is shown in Figure 1. The soil is Avondale clay loam (Fine-loamy, mixed (calcareous), hyperthermic, Anthropic Torrifluvent). Following the harvest of the sampled plants for the 1984 experiment, the remaining plants were pulled out of the soil with as many roots attached as possible. The plastic walls and air distribution tubes of the chambers were removed, but the posts, cables, and blowers remained in place. The plots were rototilled on 23 and 24 January 1985 around the chamber posts, stakes, and neutron access tubes. The soil was raked into beds for each row, but they were much lower than the ridges used with furrow irrigation. A drip irrigation system was installed, as will be described in more detail in the next section. The cotton was planted into dry soil using a one-row hand planter on 9 April, 1985, using the variety Deltapine-61 (the same as 1984) in north-south rows spaced 1 m apart.

After the cotton was planted, new polyethylene film walls and air distribution tubes were installed. The chamber design was essentially the same as described in detail in the 1983 report (Kimball et al., 1983). One change was that there were two doors in the 1985 chambers, and there were two walkways between the three rows. Also, the steel walkways were raised off the ground by 30-mm thick wood planks rather than the 200-mm high concrete blocks. The lower elevation and the additional walkway geatly facilitated flower counting, photosynthesis, and other plant measurements. Another change was that a 225-mm-diameter evaporation pan was placed at the north end of the east walkway in each chamber on a piller of concrete blocks, as will be described in more detail later.

Following chamber erection, the field was irrigated on 11 April with 50 mm of water (Table 1). Most of the cotton emerged on 16 April. The seedlings showed some signs of water stress, as the soil surface dried, so additional irrigations of about 25 mm each were applied on 22, 24, and 25 April (Table 1). On 23, 30 April, and 6 May, additional plants were transplanted into rows where germination or seedling disease had reduced the population below 10 plants/m^2. On 13 and 21 May, the plots were uniformly thinned to 10 plants/m^2. The seedlings removed by this

process were used for leaf area and dry weight determinations for these dates.

The blowers were started, and the CO_2 treatments were imposed on 2 May when the cotton was beginning to display the first true leaf. The concentrations used were ambient, 500, and 650 $\mu\ell\ \ell^{-1}$, plus the open-field plots (Figure 1). Differential irrigation treatments began on 24 May (Table 1). On a weekly schedule, the wet (or well-watered) plot received an amount of water equal to the open-pan evaporation of the previous week with an adjustment for leaf area, as will be discussed in more detail in the next section. The dry (or water-stressed) plots received 2/3 as much water as the wet plots (Table 1). On 6 June, weekly destructive sampling of the plants within each plot began. Three plants were marked each Tuesday. They were used for analysis of carbohydrates and of leaf water potential on Wednesdays and removed for leaf area and dry weight partitioning on Thursdays. Irrigations were generally done on Fridays.

Nitrogen fertilizer was applied as urea through the drip irrigation system (Table 2). A water-pressure-driven suction device was used to inject a concentrated urea stock solution into the irrigation water about half-way through each irrigation so that unfertilized water ran through the system before and after each injection. The total amount applied was 183 kg/ha (Table 2), which is a liberal application intended to prevent nutrient stress. No signs of nutrient deficiency were observed, and petiole nitrate-N analyses did not reveal any concentrations below normal for a healthy cotton crop (Table 3). There was a tendency for the plants in the CO_2-enriched plots to have lower N concentrations than those in the ambient-chamber or open field plots late in the season, however.

Insects were a problem in 1985, much more so than in the two prior years. Early in the season, thrips attacked the squares of the young plants, so spray applications of Orthene[1/] were made (Table 4). Beginning 21 June, all chambers received a weekly treatment of Vapona by placing some of the insecticide in a petri dish with a napkin wick inside each blower cabinet. In addition, certain enclosures were spot-sprayed with Kelthane for mites as needed (IIW4 on 25 June, 1 July, 8 July, 24 July; IIW3 on 24 July; and IW4 on 8 July and all plots received Kelthane on 29 July, 5 August, 12 August, 19 August, 26 August, 3 September, and 11 September). All plots received Thuricide on 12 July and 19 July for an outbreak of leaf perforator. White flies were prevalent much of the season. Control by all of these agents was only partial. The complete insecticide application history is given in Table 4.

Insects were again captured using sticky traps, and population counts were made. These data are still being reduced. However, because of the

1/ Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the listed product by the U. S. Department of Agriculture.

frequent pesticide applications (Table 4), it is unlikely that any significant relationships between insect population and CO_2 concentration can be found, in contrast to 1984 when populations of 4 insect species declined with increasing CO_2 concentration while populations of two others were unchanged by CO_2.

B. Irrigation and Water Use

A drip irrigation system was installed in 1985 to provide precise control of the water applications, as mentioned previously. Emitters (2 liters/hour at 10 m of head) were spaced every meter as it came from the factory. Anticipating that this wide spacing would not put the water sufficiently close to the plants when they were small, additional emitters were installed in the lines between each of the original factory emitters to give a spacing of 1 emitter per 0.532 m of drip line. The lines were laid down the rows adjacent to the plants. During the first irrigation, it became obvious that even with double the number of emitters, the soil midway between emitters was not adequately wetting. Therefore about halfway through each irrigation, the drip lines were all moved manually about 0.25 m down each row to improve the uniformity of wetting. The manual pulling during each irrigation continued until the plants were about 0.7 m tall and the water application amounts were large (21 June).

The well-watered (wet) plots were irrigated weekly with an amount of water determined by the formula:

$$\text{irrigation amount} = \text{pan evaporation} \times (\text{LAI}/3) \tag{1}$$

where LAI is the leaf area index determined from destructive plant harvests up to a LAI of 3. Above a LAI of 3, the irrigation amount was the pan evaporation amount of the previous week. The pan evaporation was that from a standard Class A pan located beside the field. As will be discussed later, the pan evaporation rate in the chambers was 9% less than in the open-field plots, and the pan evaporation rate in the open-field plots was 24% less than beside the field, so using this measure of Class A pan evaporation should have provided a generous estimate of the evaporative demand. Until 15 June, the LAI used in the formula was that of the day preceding the irrigation. However, visible symptoms of water stress after a week indicated that the plants were not receiving sufficient water, so after 15 June, the LAI used was a projected LAI for the forthcoming week from past weeks' data. One value of LAI was determined each week from each of the 8 wet plots. To be sure the irrigation amount was generous, the largest available LAI was used, which generally meant that the leaf area of one of the 650 $\mu\ell\ \ell^{-1}$ CO_2 chambers was used to determine the irrigation amount. As mentioned previously, the water-stressed (dry) plots received 2/3 of the amount of water applied to the wet plots.

Rainfall was also measured in gauges beside the field. Rainfall amounts were subtracted from the calculated irrigation requirement each week.

The amounts of irrigation water and rainfall applied to the wet and dry plots are plotted in Figure 2 against day of year, ignoring the initial April irrigations used for germination and stand establishment. Also plotted are the cumulative pan evaporation (x LAI/3) from Equation 1 for the wet plots and 2/3 of the wet amount for the dry plots. It is obvious from the graph that the drip irrigation system enabled us to closely track the adjusted pan evaporation curves, thereby applying the planned amount of water. The recommended water application curve from Erie et al., (1981) for well-watered cotton is also shown for the wet plots and 2/3 of the wet curve for the dry plots. The total amount of water applied over the whole season (1230 mm for the wet plots, Table 1) exceeded the Erie et al. amount (1050 mm) by 17%, indicating we were applying a generous amount of water to the wet plots. However, as results of some of the plant measurements will show, the wet plots probably could have used additional water.

Profiles of volumetric water content from the 350 $\mu\ell\ \ell^{-1}$ CO_2 plots (open-field and ambient chambers) are presented in Figure 3. Early in the season (01 May), the upper part of the soil profile was quite wet (0.34 m^3/m^3), and there was litle difference between wet and dry above 1 m. As the season progressed, the upper 1 m became drier for both dry and wet plots, but the plants in the dry plots withdrew more water from storage than those in the wet plots. By the end of the season (2 Oct), the profiles were both nearly vertical with the drys at about 0.17 m^3/m^3 and wets at about 0.22 m^3/m^3.

The total water use for each of the plots is presented in Table 5. The change in soil water storage between 17 April and 2 October was calculated from the neutron data. Comparing the seasonal change in soil water content between the wet and dry plots, the plants in the wet plots used an average of about 10 mm of water from storage while those in the dry plots used about 51 mm. There was a tendency toward greater withdrawal of stored soil moisture with increasing CO_2 concentration, but the data are somewhat scattered. Compared to the amounts of water applied by irrigation and rainfall between 20 April and 27 September, the soil storage changes are very small (about 1% for the wets and 6% for the drys). Therefore, the total water use was very close to the total amount of water applied, and differences among the CO_2 treatments amount to less than 2% (Table 5).

C. Carbon Dioxide Concentrations

CO_2 concentrations were continually monitored, as described previously in the 1983 and 1984 reports (Kimball et al., 1983, 1984). The diurnal patterns of mean CO_2 concentration for the 1985 experiment are presented in Figures 4-7. Like the previous years, it is again apparent that the ambient concentrations undergo a diurnal variation from about 350 $\mu\ell\ \ell^{-1}$ in daytime to 400 $\mu\ell\ \ell^{-1}$ at night. The enriched plots also have some diurnal variation but less pronounced because of the controlled set points at 500 and 650 $\mu\ell\ \ell^{-1}$. After sunrise each day, the concentra-

tions decreased below set points for an hour or two until the system responded to the higher level of atmospheric turbulence. Afer sunset, concentrations rose above the set points until they similarly responded to calmer night conditions.

The overall CO_2 concentration means and the standard deviations of the individual observations are tabulated in Table 6. In 1985, they averaged 363 ± 48, 367 ± 51, 507 ± 66, and 646 ± 79 $\mu\ell\ \ell^{-1}$ for the open field plots, ambient, "500", and "650" chambers, respectively.

RESULTS

A. Leaf Area, Biomass, and Yield

The accumulation of leaf area through the season is presented in Figures 8 and 9 for the wet and dry chambers, respectively. The leaf area accumulation was delayed (compared to 1984) apparently by the water stress early in the season (when the LAI used in Equation 1 was that from the past week rather than that projected for the next week). There appears to be an effect of the 650 $\mu\ell\ \ell^{-1}$ CO_2 treatment to alleviate the water stress in the dry plots prior to day 180 (Figure 9). This may explain the greater yield response of the 650-dry compared to the ambient-dry (104%) over the 650-wet compared to ambient-wet (52%, Table 7).

A comparison of the leaf-area per active boll (boll loading) through the growing season in Figures 10 and 11 shows that the dry treatments declined to minimum leaf-area:boll ratios (200-300 cm^2/boll) more rapidly and "cut-out" sooner than the wet treatmnts. "Cut-out" is indicated in the graphs by the increase in leaf area per boll which occurs when the crop ceases adding bolls to the load and reduces the active (less than 40 days old) boll number. The only treatment which did not cut-out was the 650-wet which continued flowering throughout the season.

A comprehensive tabulation of the final destructive harvest results is presented in Table 7. The dry weight was increased by 40 and 51% by CO_2 enrichment to 500 and 650 $\mu\ell\ \ell^{-1}$, respectively, in the wet plots. In the dry plots, the dry weight stimulation amounted to 52 and 71% at 500 and 650 $\mu\ell\ \ell^{-1}$ CO_2. The relative CO_2 stimulation of seed cotton yield (lint + seed) was 45 and 52% at 500 and 650 $\mu\ell\ \ell^{-1}$ CO_2 enrichment, respectively. In the dry plots, seed cotton yield was increased even more, by 64 and 104% at 500 and 650 $\mu\ell\ \ell^{-1}$, respectively. There was little effect of CO_2 on % lint per boll, on seed index, or on harvest index (Table 7). There was a reduction in harvest index in the dry plots in contrast to the effect in 1984. The severity and season-long duration of the stress in 1985 compared to that in 1984 probably explains the change.

The seed cotton yields for the past three years are plotted together in Figure 12. The 1985 yields from the wet plots were lower than those from 1984, a trend reported widely by other researchers and farm obser-

vers. The 1985 yields from the ambient chamber - dry plots were the lowest we have observed, indicating that the water-stress treatment was administered precisely with the drip irrigation system as desired.

In Figure 12, the yields from the dry plots appear to be interspersed among those from the wet plots, indicating no significant interaction between CO_2 response and water stress. However, the high yields from the dry plots in 1984 can be attributed to poor water application control from flood irrigation and unusually high rainfall. Therefore, 1985 was the only year with a well-controlled water-stress treatment, and the relative yield increases from CO_2 enrichment (upper graph) were higher for the dry plots than the wet plots in 1985. Thus, our better 1985 data suggest there may be a positive interaction between CO_2 enrichment and water stress, but the 1984 data do not. A positive CO_2-enrichment, water-stress interaction would be consistent with the results of some other prior experiments with other crops that have reported a somewhat greater response to CO_2 under water-stressed than under well-watered conditions.

Focusing on the upper graph in Figure 12 of relative yields, it is obvious that cotton is highly responsive to increases in atmospheric CO_2 concentration. A near-doubling of CO_2 (650 $\mu\ell\ \ell^{-1}$) produced yield increases ranging from 44 to 134% with an average (from the regression line) of 80%.

B. Flower Production and Boll Retention

Flowers were counted and tagged daily on the day of anthesis except for weekends and on 4 and 8 July. The tags were recovered, sorted, and counted at the end of the season. The data in Tables 8-14 do not include interpolated values.

More flowers were produced in the ambient chambers than in the open plots (Table 8). CO_2 enrichment greatly increased the number of flowers produced, with the effect being more in the dry (+103% at 650 $\mu\ell\ \ell^{-1}$) than in the wet (+64% at 650 $\mu\ell\ \ell^{-1}$) plots. Except for the ambient chambers, water deficit had virtually no effect on the number of flowers produced.

In the wet treatment more bolls were produced in the ambient chambers than in the open plots, but not in dry treatment (Table 9). CO_2 enrichment increased the number of bolls produced, but the increase between 500 and 650 $\mu\ell\ \ell^{-1}$ CO_2 was relatively small. Water deficit decreased the number of bolls produced, and the effect was much greater in the chambers (70 to 80% reduction) than in the open (17% reduction).

Although CO_2 enrichment increased flowering, it did not increase boll retention percentage (Table 10). Water deficit decreased boll retention, especially inside the chambers. Boll retention rates inside the chambers were extremely low through day of year 207 (26 July) in the dry

plots (Tables 13 and 14). Retention rates were much better in the open than in the chambers. Something happened during the week of 210 through 214 (29 July through 2 August); the dry chamber plots set almost half of all of their bolls during that one week because of abrupt increases in flowering and retention (Tables 13 and 14). The same changes occurred in the wet plots, but were not as pronounced (Tables 11 and 12).

Water deficit was a dominant feature and cause of poor fruit retention early in the season. The small plants were unable to set many bolls, especially in the dry plots. Boll retention in the dry plots was the lowest we have ever measured.

C. Photosynthesis at Chamber Concentrations

Net leaf photosynthesis at midday was measured in all of the plots on seven clear days during the 1985 season, usually 3 or 4 days following an irrigation. Two instruments were used: 1. A Li-Cor Model 6000 Portable Photosynthesis System and 2. an Analytical Development Co. (ADC) Portable Photosynthesis System, which consists of a Model LCA-2 CO_2 analyzer, Model PLC leaf cuvette, and Model ASU air pump. The Li-Cor is a transient measurement device because it calculates the photosynthetic rate from the decline in CO_2 concentration after a sealed chamber is clamped on a leaf. It can similarly measure transpiration and stomatal resistance from the rate of increase of relative humidity inside the chamber. The ADC, on the other hand, is a steady-state instrument in that it measures the drop in CO_2 concentration of an air stream flowing through a small leaf chamber.

At ambient air temperatures below 40C, both instruments appeared to work well. Above about 40C, the Li-Cor became erratic and would not sustain a calibration, so we taped bottles of "blue ice" to the console and under the CO_2 analyzer before each run. The whole package was placed inside a styrofoam half-box for shading. With this extra cooling, the Li-Cor appeared to give reliable results. The ADC was generally stable even when ambient air temperatures were above 45C. However, the liquid crystal display would blank-out if left in the sun, so it was necessary to continually shade this instrument also.

The usual sampling procedure was for two operators to each take one of the instruments and sample all chambers. They would start in plot IW1, each randomly sampling 3 sunlit leaves from the top of the canopy in the center row. Usually, the youngest fully expanded leaf on a plant was selected, which would be the 4th or 5th from the apex of a branch. The operators did not use the same leaves for both instruments, so in fact usually six leaves were sampled per plot on each sampling day.

The results were analyzed first by pairing observations from the same treatments obtained at close to the same time for the two instruments. The mean of 255 observations with the Li-Cor was 28.8 μ mole $m^{-2}s^{-1}$ while that with the ADC was 32.2 μ mole $m^{-2}s^{-1}$ or about 12% higher. Our

analysis of variance showed that these means for the two instruments were significantly different at the 0.001 probability level. Possibly the Li-Cor was systematically measuring at a lower CO_2 concentration. The software in the system computed the photosynthesis rate at the beginning of the measurement period (about 20 sec for 10 CO_2 concentration observations), but the measurement period wasn't usually started until about 10 sec after the chamber was clamped on a leaf. However, the CO_2 concentration did not decrease nearly 12% in these few seconds, so it is unlikely that this can be the full explanation for the difference between the Li-Cor and the ADC.

An analysis of the variance due to the treatments was performed next. The data from the Li-Cor and ADC were considered as additional replicates, as were the successive samplings over the several days during the season. Some data were discarded because of various problems leaving 69 observations of net leaf photosynthetic rate for each irrigation-CO_2 treatment combination. The data were analyzed using a split plot analysis of variance with irrigation as the main plot and CO_2 treatment for the sub-plot.

The results of the analysis of variance are presented in Table 15. The interaction between irrigation and CO_2 treatment was not significant. The average leaf net photosynthetic rate was only about 10% higher on the average in the wet plots than in the dry plots for these data usually taken 3 or 4 days after an irrigation. There was no significant difference between the plants in the open field plots and those in the ambient chambers. The mean net photosynthetic rates in the ambient, 500, and 650 $\mu\ell\ \ell^{-1}$ CO_2 chambers were 22.8, 36.6, and 40.4 μ mole m^{-2} s^{-1}, so CO_2 concentration had a large significant effect. The 77% increase of the plants in the 650 $\mu\ell\ \ell^{-1}$ chambers over those in the ambient chambers is comparable to the increases in biomass accumulation and seed cotton yield (Table 7).

D. Photosynthetic Responses to Changes in CO_2 Concentration

Photosynthesis was measured at varying CO_2 concentrations on plants in the ambient and 650 $\mu\ell/\ell^{-1}$ chambers using the portable photosynthesis system (Analytical Development Co.), briefly described in the previous section. The system includes a constant-flow air pump, a clip-on cuvette for single-leaf gas exchange, and a compact infrared CO_2 analyzer. The CO_2 source was a cylinder of air containing about 2000 $\mu\ell/\ell$ CO_2. This gas was divided into two streams by an adjustable valve on the air pump. One of the gas streams was scrubbed of its CO_2 by passage through soda lime columns, after which it was recombined with the unaltered gas stream. Control of CO_2 concentrations was easily achieved over the range of 0 to 1000 $\mu\ell/\ell$.

Stomatal conductances were determined with a LiCor LI-1600 steady-state porometer. Three leaves were measured both before and after the series of measurements of photosynthesis. In those few cases in which conduc-

tance changed during a run, values were linearly interpolated to estimate conductances at the actual times of the photosynthesis measurements. The conductances thus estimated were used to calculate internal CO_2 concentration (c_i) at any given external concentration (c_e). Photosynthesis rate (A) was plotted as a function of c_i. This method depends upon the rapid attainment of a steady state in the gas exchange system, so that the stomata have too little time to react to altered c_e in the cuvette. The typical time needed for the attainment of a steady state was 20 seconds. All measurements were made in the late morning (0930-1200 hours). The relationships between A and c_i were estimated by quadratic regressions.

To distinguish between the changeable test CO_2 concentration and the chamber CO_2 concentration at which the plants were grown, we shall refer to the chamber concentration as the "growth" CO_2 concentration. In general, there was no effect of growth CO_2 concentration on photosynthetic capacity or photosynthetic response to CO_2 until very late in the season. During July and August, the $A(c_i)$ curves for plants grown at ambient CO_2 and 650 $\mu\ell/\ell$ were virtually identical. With well-watered plants, the curves were notable for their failure to show saturation of photosynthesis with respect to CO_2 except at extremely high c_i (Figures 13, 14, 15). Photosynthesis of water-stressed plants did show saturation at much lower c_i during the same period, but the curves were again little affected by CO_2 concentration. In mid-September, the pattern was quite different. At this time, growth at 650 $\mu\ell/\ell$ CO_2 significantly decreased photosynthetic response to CO_2 below that of plants grown at ambient CO_2.

Stomatal conductances were very high in well-watered plants during July and August (Tables 16, 17, 18), and were almost unaffected by growth CO_2 level. Water stress increased stomatal sensitivity to growth CO_2 level. In September, when daytime temperatures were much cooler than in July and August, conductance was much lower in accordance with known responses to temperature.

These data provide a firm basis for interpreting the large yield response of cotton to CO_2 increases. The very high stomatal conductances, even at high CO_2, allow extremely rapid entry of CO_2 into the leaf. The linear response of photosynthesis to c_i, and the failure of high CO_2 to depress photosynthetic capacity, ensure that the plentiful supply of CO_2 is used efficiently for photosynthesis. The conditions which promote this great response to CO_2 are present for most of the season, and may be related to the very high temperatures during the day. Enriched CO_2 (650 $\mu\ell/\ell$) increased the photosynthetic rate by 75% at midseason in the wet plots (Table 16), in excellent agreement with the other photosynthesis measurements at chamber CO_2 concentrations (Table 15). In the dry plots, water stress apparently caused saturation at lower c_i (Figure 13), which apparently decreased the CO_2 promotion of photosynthesis to 43% (Table 16), although the longer term measurements at chamber CO_2 concentration do not show such a reduction (Table 15). The measurements

of photosynthetic response to changes in CO_2 (Tables 16, 17, 18) were all taken near the ends of the weekly irrigation cycles, when water stress was maximal, whereas the long-term measurements (Table 15) were made sooner after the irrigations. This difference in days following irrigation that the measurements were taken may explains the different effects of stress found by the two methods. In any event, these increases in photosynthesis, due to CO_2 enrichment, are quite consistent with the yield increases (Table 6).

E. Diurnal Variation of Carbohydrates

A study was conducted to determine how the concentration of leaf carbohydrates varies diurnally and how it would be affected by the CO_2 and irrigation treatments. Mature, fully expanded leaves from field-grown cotton plants in varying aerial CO_2 enrichments and irrigation treatments were sampled at dawn (6:30 AM) by punching six one-cm discs with a cork borer. These discs were immediately placed in ice-cold 80% ethanol and quickly moved to a -85°C freezer for storage prior to analysis. Six smaller discs (ca. 0.28 cm^2) were also taken for anatomical analysis and placed into ice-cold fixative (FAA) consisting of 90 parts 50% ethanol, 5 parts glacial acetic acid and 5 parts formalin solution. The anatomical samples were infiltrated by quickly transferring them to a vacuum for 30 sec. Both samplings were repeated at the end of the photoperiod (7 PM). The dawn and predarkness sampling times were chosen to correspond to the daily maximum and minimum of cotton leaf starch (Hendrix and Huber, 1986). These samplings took place near the end of the season, on 29 August 1985.

The anatomical sections were infiltrated with n-butyl alchohol followed by paraffin wax for microtoming in a standard manner. The resulting sections were stained by the periodic acid-Schiff method for starch and counterstained with aqueous toluidine blue O for cellular detail. Under these conditions, starch grains are bright red against a green to blue cellular background.

Carbohydrate samples, immersed in 4 ml of 80% ethanol, were transferred directly from -85°C to a 80°C water bath for 25 min and then ground with a Brinkman Polytron equipped with a PT-10 generator. Following centrifugation, the insoluble matter was re-extracted three times with 80% ethanol at 80°C for 15 min. Aliquots of the resulting alcohol extract were evaporated and analyzed enzymatically for sucrose, fructose and glucose by following the change in absorbance of NADP at 340 nm in the presence of glucose-6-P dehydrogenase, hexokinase, phosphoglucose isomerase, invertase and ATP, as appropriate. Starch in the residue was similarly determined as glucose, following digestion of the residues by amyloglucosidase.

The long-term chronic exposure to elevated aerial CO_2 in either dry or wet soils strongly promoted starch accumulation in the cotton leaves (Table 19). It is clear that these elevated levels of starch were not

the result of elevated rates of synthesis as much as they were due to the lack of complete breakdown during the subsequent dark period. Under dry conditions, for example, starch levels at dawn differed strongly with CO_2 levels (8 to 98 mg/dm^2) but the amount of starch synthesized during the day was approximately the same in all CO_2 regimes (ca. 30 mg/dm^2). The 'wet' series exhibited the same pattern except that the amount of starch synthesized during the day was twice as great (ca. 70 mg/dm^2). The wet treatment with 650 ppm CO_2 may be an exception in that it synthesized at a somewhat slower rate than the two lower CO_2 regimes; however, this could well have been due to a physical limitation upon the starch synthesizing mechanism within chloroplasts already filled with tremendous amounts of starch (115 mg/dm^2) at the start of the light period.

Visual observations of leaf sections confirmed the chemical analysis. The starch grains were found to be widely distributed across both mesophyll layers in cotton leaves and were shown to be very abundant in all slides except for those sampled in ambient air and dry soil at dawn. Elevated CO_2 and changing soil water status had little effect on ethanol-soluble carbohydrates; we often find no fructose in cotton tissue.

The amount of starch added to cotton leaves during a single photoperiod seemed to be governed by the water status of the plants. The 'residual' level of starch in cotton leaves upon which these daily syntheses built seemed to depend upon aerial CO_2 concentrations.

There have been reports in the literature (Mauney et al., 1979, for example) describing a decline in photosynthetic rate after long-term exposure to high CO_2, and such declines have been blamed on high starch accumulation at high CO_2. Therefore, the photosynthetic results in the previous two sections along with these starch results are somewhat surprising. The photosynthesis data showed that high photosynthetic rates were maintained at high CO_2 in cotton plants acclimated to high CO_2, and these starch results (Table 19) show that this high photosynthetic rate was maintained in spite of high starch contents. Thus perhaps another mechanism must be postulated to explain the photosynthetic decline in the other studies.

F. Stomatal Resistance

Stomatal resistance at midday was measured in all of the plots on seven clear days during the 1985 season. They were determined with the Li-Cor Model 6000 Portable Photosynthesis System simultaneously with the net photosynthesis measurements described in Section C. Briefly, three sunlit leaves near the top of the canopy were randomly selected from the center row of each plot, which together with the two replicates in the experimental design (Figure 1) gave 6 observations per day per irrigation-CO_2 treatment combination. The observations for the several days were handled as additional replications for the statistical analy-

sis. Discarding some data due to various instrument problems, a total of 39 observations were available per treatment combination. There was a significant interaction between the CO_2 and irrigation treatments, so the data from the wet and the dry plots were analyzed separately.

The mean stomatal resistance and their corresponding standard deviations are presented in Table 20. The upper portion of the table shows the means for all days for which stomatal resistance data were available. There was no significant difference (.05 probability level) between the plants in the open field plots and those in the ambient chambers in the dry irrigation treatment. However, in the wet irrigation treatment, the open field plants had a surprisingly higher (63%) stomatal resistance than those in the ambient chamber. As expected, the stomatal resistance of the plants in the dry chamber was higher by 150% than those in the wet chamber. In both the dry and wet treatments, the plants in the 650 $\mu\ell\ \ell^{-1}$ chambers had significantly higher resistances than those in ambient chambers (69 and 47% higher for the dry and wet treatments, respectively) with 500 $\mu\ell\ \ell^{-1}$ plants in between.

There appeared to be some increase in stomatal resistance with time after an irrigation even in the wet plots, so to get the best estimate of the minimum stomatal resistances on well-watered cotton, those data obtained within 4 days of an irrigation were selected for separate analysis. Comparing the data for the two wet rows in Table 20, the average resistances within 4 days of an irrigation were about 30% lower than the averages for all of the days which included data from two days that were 5 or 6 days after an irrigation. Thus, on the day before these particular weekly irrigations, the plants in even the wet plots were exhibiting stomatal closure associated with some water stress. The effect of CO_2 on these within 4 days of irrigation data was similar to that in the other irrigation categories, with the plants in the 650 $\mu\ell\ \ell^{-1}$ CO_2 chamber having a significantly higher (30%) stomatal resistance than those in the ambient chamber with the 500 $\mu\ell\ \ell^{-1}$ plants in between.

G. Leaf Temperatures

Increasing the atmospheric concentration of carbon dioxide (CO_2) tended to induce partial stomatal closure as shown in the previous section (Table 20). One important side effect of this phenomenon should be higher foliage temperatures; for the excess heat load on the plant leaves resulting from the decreased efficiency of latent heat removal under these conditions can only be dissipated by increases in the magnitudes of convective and radiant heat transfer processes, which are primarily brought about by an increase in foliage temperature.

Foliage temperatures were measured on most cloudless days of the past three years at about 13:30 MST with an Everest Interscience infrared thermometer. In 1983, each data point acquired represented the mean of twenty separate measurements taken over the center of each chamber's middle row. Data acquisition in 1984 and 1985 was similar, but with ten

observations taken from each of the east and west sides of the middle row. In all cases, the infrared thermometer had a slight tilt from the vertical; and in each year a different person collected the data.

Insufficient data were acquired on the moderately dry plots to be able to say anything about effects of atmospheric CO_2 enrichment on cotton. Thus, in what follows, all data presentations pertain to times when the plants were well supplied with water and transpiring at the potential rate.

Figure 16 shows the results obtained in 1985. The solid lines (which are identical on all three data-containing sections of the figure) represent the "non-water-stressed baseline" (Idso, 1982) for cotton growing under ambient CO_2 conditions (340 ppm by volume). It is derived from the equation

$$T_F - T_A = \frac{r_A R_N}{\rho c_p} - \frac{e_F^* - e_A}{\gamma(1 + r_{FP}/r_A)} \qquad (2)$$

where T_F is foliage temperature (°C), T_A is air temperature (°C), R_N is net radiation (Wm^{-2}), e_F^* is the saturated vapor pressure (kPa) at the temperature of the foliage, e_A is the actual vapor pressure of the air (kPa), ρ is the air density (kg m^{-3}), c_p is the air heat capacity (J kg^{-1} °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), r_A is the aerodynamic resistance of the plants to sensible heat transfer (s m^{-1}), and r_{FP} is the plant foliage resistance to water vapor transport under conditions of potential transpiration (s m^{-1}). For the specific baseline shown in Figure 13, R_N was set equal to 525 Wm^{-2}, which was typical of the season and time period over which T_F, T_A and air vapor pressure deficit (VPD) data were collected, r_A was set equal to 15 s m^{-1}, the value experimentally determined to be appropriate for cotton by Idso et al., (1986a), and r_{FP} was set equal to 25.0 s m^{-1}, the mean value found to pertain to ambient CO_2 conditions by Idso et al., (1986a). For comparison, the lower right-hand section of Figure 16 also depicts non-water-stressed baselines for r_{FP} values of 29.6 and 35.8 s m^{-1}, which represent adjustments to the ambient value of 25.0 s m^{-1} which we determined to be appropriate for the 500 and 640 ppm CO_2 treatments as a result of our 1984 and 1985 stomatal diffusion resistance measurements.

Concentrating first on the lower right-hand section of Figure 16, it can be seen that the vertical separation of the three CO_2-treatment baselines is small. Averaged over the air VPD range 0.0 to 6.4 kPa, for instance, a mean foliage temperature increase (ΔT_F) of only 0.53°C is predicted for the 340 to 500 ppm transition in atmospheric CO_2 concentration, while a further T_F increase of only 0.66°C is predicted for the subsequent 500 to 640 ppm atmospheric CO_2 concentration transition. Consequently, it can be appreciated from viewing the rest of the figure

that we are looking for a CO_2-induced foliage temperature response which is much smaller than the magnitude of noise inherent in the actual T_F, T_A data. Nevertheless, in observing the changing relationship between the $r_{FP} = 25.0$ s m^{-1} non-waterstressed baseline and the $T_F - T_A$ vs. VPD data as the atmospheric CO_2 concentration increases from 340 to 500 to 640 ppm, it is evident that an antitranspirant effect on the order of this magnitude is indeed present.

To ferret out this T_F dependency of cotton on the atmospheric CO_2 concentration, we determined the mean deviations of all data points in each CO_2 treatment from the $r_{FP} = 25.0$ s m^{-1} baseline and plotted the results as a function of the atmospheric CO_2 content, as in Figure 17, where we also included the results of this same procedure applied to the 1983 and 1984 data. As can be seen there, all three years show monotonically increasing foliage temperatures with increasing atmospheric CO_2. In addition, the mean T_F/CO_2 response--as determined by linear regressions run on the mean results between CO_2 concentrations of 340 and 500 ppm and 500 and 640 ppm--is nearly identical to that predicted by equation (2) utilizing our measured values of r_{FP} under CO_2-enriched conditions: a measured ΔT_F of 0.43°C vs. a calculated value of 0.53°C for the 340 to 500 ppm atmospheric CO_2 concentration transition, and a measured ΔT_F of 0.56°C vs. a calculated value of 0.66°C for the 500 to 640 ppm CO_2 transition. Consequently, we conclude that there is a real, but rather small, effect of atmospheric CO_2 enrichment on cotton foliage temperature, such that a nominal 300 to 600 ppm doubling of the atmospheric CO_2 content would produce about a 0.88°C increase in cotton foliage temperature (obtained by utilizing the slope of the 500 → 640 ppm relationship of Figure 17 for the 500 → 600 ppm portion of this transition, the slope of the 340 → 500 ppm relationship for the 340 → 500 ppm part of the transition, and a slope which is reduced in magnitude from the 340 → 500 ppm relationship by an amount equal to the difference between the 500 → 640 ppm slope and the 340 → 500 ppm slope for the 300 → 340 ppm part of the transition).

Further confidence in this conclusion is provided by Figure 18, where we have plotted calculated CO_2-induced foliage temperature increases vs. measured CO_2-induced foliage temperature increases: a) for cotton, as determined from this study, and b) for water hyacinth--the only other plant so studied to date--as determined, in the case of the measured values, by the study of Idso et al. (1986b), and, in the case of the calculated values, by the study of Idso et al. (1984), which produced the appropriate r_{FP} values for the enriched CO_2 treatments, and the study of Idso et al. (1986a), which produced the appropriate r_A value. In all five comparisons there depicted, there is very good agreement between calculated and measured results.

Using the value of 0.88°C for the foliage temperature rise, we can calculate the per-unit-leaf-area plant transpiration rate reduction expected in cotton for a 300 to 600 ppm doubling of the atmospheric CO_2 content under the mean conditions of the three years of our experiment.

Again, the appropriate value for R_N appears to be 525 Wm^{-2}; but for the air VPD, a mean value of 3.6 kPa is seen to prevail when all of the data are considered. For this air VPD value, Fig. 3 of Idso et al. (1986a) yields a mean T_A of 32.0° C; and, following the above procedure with these input parameters, we calculate an IJ index of 0.073, which implies a CO_2-induced decrease in per-unit-leaf-area plant transpiration rate in cotton of 7.3 percent. A 7.3% reduction in leaf transpiration rate is within the 4-9% reduction in water use per unit of land area due to a doubling of CO_2 as measured with lysimeters in 1983 (Kimball et al., 1983). However, other water use per unit of land area measurements in 1983, 1984 (Kimball et al., 1984), and 1985 (Table 5, this report) using neutron apparatus have not shown a decrease. Rather it appears that the increase in leaf area with increasing CO_2 can more than offset a 7.3% reduction in leaf transpiration.

It is logical to hypothesize that a plant which does not close its stomates as much as another in response to an increase in atmospheric CO_2 content will probably have a greater photosynthetic or yield response to that atmospheric CO_2 enrichment than the other [so long as the A (C_i) curve does not flatten out and saturate (figure 13, 14, and 15)]. Furthermore, since reductions in yield correlate linearly with the IJ index (Idso et al., 1981; Diaz et al., 1983; Pinter et al., 1983), it is logical to assume that such relative increases would likewise correlate linearly with the relative IJ index responses of the two crops in question. That is, we feel it is a logical consequence of prior IJ index/crop yield studies to expect the yields of two crops (Y_1, Y_2) to be related to their CO_2-induced IJ index values (IJ_1, IJ_2) in the following way, as a result of an increase in atmospheric CO_2 concentration:

$$\frac{Y_1}{Y_2} = \frac{IJ_2}{IJ_1} \tag{3}$$

As a test of this hypothesis, we predict the yield increase of cotton (Y_c) caused by a 300 to 600 ppm doubling of the atmospheric CO_2 concentration to be $Y_c = Y_{WH}$ (0.178/0.073), where Y_{WH} is the percentage yield increase of water hyacinths caused by such a CO_2 concentration doubling, which Idso _et al_. (1985) have experimentally determined to be 35.6 percent (from their Fig. 1). Our predicted CO_2-induced yield increase for cotton, then, is 86.8 percent, which is in excellent agreement with the measured yield response of cotton for such a CO_2 concentration increase from 300 to 600 $\mu\ell\ \ell^{-1}$ over the three years of our experiment (Figure 12) of 86.2 percent. Consequently, we take this good correspondence between calculated and measured yield response to provide strong support for the validity of equation (3).

H. Leaf Water Potential and Relative Water Content

Leaf samples were taken one day a week during the months of June through August for pressure-volume analysis-that is, leaf water potential as a

function of relative leaf water content (Figure 19). The samples were taken just before dawn and near mid-afternoon (i.e. from 12:00 noon to 2:00 p.m.) either five or six days after each weekly irrigation when any water stress effects should have been maximal. One leaf was taken from each plot (or chamber) within one replicate (rep) each sampling time to make a manageable batch of 8 leaves. Sampling alternated between the reps with successive samplings. A plastic Zip-loc bag was humidified with a breath of air just before the youngest fully expanded leaf from a plant, usually the fourth or fifth leaf from the shoot apex, was severed with a razor blade and then sealed in the bag. Care was taken to shade the desired leaf in order to cut down on further leaf transpiration. The bags were then stored under a wet towel in a Styrofoam chest for immediate transport to the laboratory.

Once inside the laboratory, the leaves were weighed, and then their petioles were placed in beakers of distilled water to hydrate them. A plastic tent and an opaque cover were placed over them to produce a dark, saturated atmosphere. The leaves were allowed to hydrate for 16 to 24 hours in a constant temperature room at 23 degrees Celsius.

After hydration was stopped, the leaves were re-weighed to obtain their saturated weight. They were then placed and sealed in fresh Zip-lock bags. Data consisting of water potential measurements and accompanying leaf weights were obtained in the following manner. One by one the leaves were placed in a Scholander bomb (Soil Moisture Equipment Corp., Model 3000) for water potential determination. They were wrapped with the plastic bag with only their petiole protruding. The pressure in the bomb was increased with compressed N_2 at a rate of 0.03-0.07 MPa/s until sap began to exude from the petiole. Generally, the pressure was noted when at least three droplets of moisture exuded from separate strands of xylem on the cut petiole's surface. The weight of the leaf was then taken immediately after the water potential measurement. This process was then repeated with another leaf. Between weighings and pressure bomb readings, the leaves were allowed to lose water, transpiring in a dark, dry drawer. Since weight loss via transpiration decreased with time, increasing amounts of leaf area were allowed to protrude from the bags. About eight pressure-weight points were obtained on each leaf, or at least enough to ensure that graphs of reciprocal pressure potential versus weight loss had become linear so that the potential at zero turgor could be determined, as will be discussed later. Approximately five hours were required to process each batch of leaves.

After the pressure-bomb weighing runs were completed, the petioles were severed from the leaf blades, and the blade and petiole fresh weights were measured. The leaf blades and petioles were then dried in an oven at 70 degrees Celsius for at least 24 hours and weighed. Relative leaf water contents-(RLWC,%) were then computed from

$$RLWC = \frac{(B_f - B_d)100}{B_s - B_d}$$

$$= \frac{(L_f - P_f - B_d)100}{L_{ts} - P_s - B_d} \tag{4}$$

where B_f is the fresh leaf blade weight, B_s is the saturated leaf blade weight, B_d is the dry leaf blade weight, L_f is the fresh weight of the entire leaf, L_{ts} is a "true" final hydrated weight after a long period of hydration, P_f is the fresh petiole weight at the time of a particular water potential reading, and P_s is the saturated petiole weight. The P_f, P_s, and L_{ts} in Equation 4 could not be measured expediently, so two ancillary experiments were performed to produce formulas for their approximation. The experiment conducted to determine the proportion of leaf water loss that was from the leaf petioles rather than the leaf blades and thereby obtain P_f and P_s was as follows. Sixteen leaves were sampled (8 from the wet plots, 8 from the dry plots) and all leaves were hydrated for 24 hours. Eight potential-weight points were obtained from eight of the leaves (4 from the dry and 4 from the wet plots), while the other eight remained untested. The final fresh weights of the tested leaves' petioles and the saturated weights of the untested leaves' petioles were taken. The results showed that the petiole weights at saturation averaged 1.2414 times more than the petiole weights after completion of the pressure-weight runs. Assuming that the petiole water losses occur proportionally to the water losses from the leaf blades, the fresh petiole weights in Equation 4 were calculated from:

$$P_f = P_{ff} \left[1 + \frac{0.2414(L_f - L_{ff})}{(L_s - L_{ff})} \right] \tag{5}$$

where P_{ff} and L_{ff} are the final fresh petiole and leaf weights, respectively at the completion of the potential-weight curves. The P_s for Equation 4 was calculated using L_s for L_f in Equation 5.

The other ancillary experiment was conducted to determine the amount of time required to fully hydrate the leaves. Eight leaves from one rep were harvested and their field weights were taken. The leaves were then placed in distilled water to hydrate. After an initial 15 hours of hydration, the weights of the leaves were taken every 3 hours of each working day for three days. The data points from wet and dry plot leaves were plotted on different graphs of percent saturation versus time (hours). Each set of data points yielded a curve of form:

$$L_s/L_{ts} = 1 - a\,[\exp(-bt)] \tag{6}$$

where a,b are constants, t is time (hours), and L_s is the hydrated weight at time t, and L_{ts} is the final "true" saturation weight after infinite hydration time. The hydration curves for leaves from the wet and dry plots were significantly different, so two separate equations

were developed. The constants were fitted by eye to the data, and the values obtained were a=0.1672 and b=0.0681 for the wet plots, and a=0.2663 and b=0.0855 for the dry plots. As mentioned previously, the normal hydration times were 16 to 24 hours. Therefore, the ratio, L_s/L_{ts} ranged from 0.94 to 0.97 for the wet plots and from 0.93 to 0.97 for the dry plots. In other words, the leaf weight, L_s, after the normal 16 to 24 hours hydration period was divided by the correction factor or ratio L_s/L_{ts} from Equation 6 to obtain the "true" saturated leaf weight, L_{ts}, for computation of RLWC from Equation 4.

After computation of relative leaf water content (Equation 4) and reciprocal pressure for each data point for each leaf, "pressure-volume" curves such as shown in Figure 19 were plotted for each leaf, following Radin and Parker (1979) for example. From water relations theory, the curved upper portion of the graph results from the existence of positive turgor pressure along with the osmotic pressure, whereas the lower linear portion reflects only the osmotic pressure with zero turgor. The intersection of the upper curve with the lower line is the zero turgor point, as indicated in Figure 19, and theoretically is the point of incipient wilting. However, we often sampled leaves that did not appear wilted, but that later were determined to have had lower relative leaf water contents than that at the zero turgor point.

While the significance of the various parts of the curve in Figure 19 are well-documented, the actual drawing of curves based on 8 data points was quite subjective. Therefore, some of the variance in the data based on the vital points of the P-V curve were due to human error, as well as plant to plant variability.

To facilitate comparisons among the numerous pressure-volume curves, three points from each curve were digitized and tabulated. As indicated in Figure 19, the three points were: (1) the zero turgor point, (2) the intersection of the curve with a 1.5 MPa line, and (3) the field sampling point. The first point was determined by the break from linear to curvilinear, the second by where the curve (or line) crossed 1.5 MPa, and the third by where the RLWC at time of sampling (determined from the initial field fresh weight) crosses the P-V curve (or line).

There were a total of 10 sampling days throughout the summer. Out of these 10, data from six days were selected when experimental conditions (e.g. weather and especially time after irrigation) were uniform and optimal. On these six days, leaves from wet and dry plots for the four CO_2-chamber treatments were obtained both at predawn and afternoon. The data were statistically analyzed using days for reps, irrigation as the main plot, CO_2 as the sub-plot, and time of sampling as the sub-sub-plot.

The results are presented in Figures 20 and 21 with respect to 1) CO_2 concentration, 2) irrigation, and 3) sampling time. Focusing first on the osmotic potential at zero turgor, there were no statistical dif-

ferences between these plots due to the CO_2 or irrigation treatments. This finding is consistent with the carbohydrate concentration data (Table 19) which show that the concentrations of soluble carbohydrates (glucose, sucrose, fructose) were not affected by CO_2 or irrigation treatments. On the other hand, starch concentrations were greatly increased by increasing CO_2 concentration, but starch is insoluble, so apparently osmotic potential was not affected by such an increase.

The osmotic potential at zero turgor was affected by the time of day, as evidenced by the statstically significant difference between leaves sampled after noon (2 p.m.) and those sampled at predawn (5 a.m.). This difference is evidence of a diurnal pattern of osmotic cycling consistent with the sucrose concentration differences between 6:30 a.m. and 7:00 p.m., as presented in Table 19. Radin et al. (1986) have similarly observed diurnal cycling of the osmotic potential at zero turgor in cotton plants, and they present evidence to suggest that the amplitude of such cycling is positively correlated to the source/sink ratio of the plants.

The RLWC at zero turgor was not significntly affected by the CO_2 concentration in the plots with chambers, nor was there any significant difference between the open field plots and the ambient-CO_2 chambers (Figure 20). However, there was a significant 1.5% decrease in RLWC in the dry compared to the wet plots. This difference suggests that the plants in the dry plots have less water in their leaves at the point of incipient wilting, and therefore presumably could carry on some photosynthetic activity with open stomates at drier conditions than those plants which experienced less water stress in the wet irrigation treatment. There also was a small (3%) decrease in RLWC at zero turgor in the midday (2 p.m. in Figure 20) samplings, as compared to the predawn (5 a.m.). This daily cycling of RLWC at which zero turgor occurs, is apparently related to the diurnal cycling of osmotic potential already discussed. In Figure 19, if the straight line shifts downward, as it does in the afternoon, then the intersection with the curved upper portion would be expected to intersect at a somewhat lower RLWC.

The relative leaf water content data at 1.5 MPa were very similar to the RLWC data at zero turgor (Figure 20), except the difference due to time of sampling was smaller and not statistically significant. However, the comments above (for RLWC at zero turgor) apply also to RLWC at 1.5 MPa.

The data in Figure 20 suggest that despite the numerous changes that do occur in cotton due to different concentrations of CO_2, such differences do not significantly change the relationship of RLWC vs. water potential. Thus, there was no major shift in this curve due to different CO_2 concentrations in the open-top enrichment chambers, nor was there any shift due to the chambers themselves (comparing open field vs. ambient chamber). However, the dry treatment did cause a small (2%) decrease in RLWC, and there was diurnal cycling of osmotic potential at zero turgor, as had been observed previously. Figure 21 shows the mean relative leaf

water contents at the time of sampling, as determined from the initial weights of the leaves. Also shown are the leaf water potentials corresponding to these RLWC's on the P-V curves for each individual leaf. There was a significant decrease in RLWC (5.4%) and in leaf water potential (0.04MPa) in the plants in the 650 $\mu\ell\ \ell^{-1}$ chambers compared to the ambient chambers, with the plants in the 500 $\mu\ell\ \ell^{-1}$ chambers in-between. However, there were no siginificant differences between the ambient chamber plants and those in the open field plots. The dry irrigation treatment caused a significant decrease in RLWC (5.6%) and in water potential (0.5MPa), compared to the wet plots. Similarly, there were significant decreases in the midday samplings compared to the predawns for both RLWC (6.5%) and leaf water potential (0.7MPa). The decreases in RWCL and leaf water potential in the field due to the dry irrigation treatment compared to the wet and to the midday sampling compared to the predawn were expected. However, the decreases in RLWC and leaf water potential with increasing CO_2 concentration were somewhat of a surprise. The increased CO_2 concentration tends to partially close the stomates (Table 20), and therefore the increased CO_2 might be expected to enable the leaves to maintain higher leaf water contents. However, the increased CO_2 also caused increases in leaf area of the plants (Figures 8,9). In spite of the partially closed stomates, the increased leaf area caused the high-CO_2 plants to use about the same amount of water per unit of land area (Table 5), and therefore they depleted the soil water available to them about as fast as the ambient-CO_2 plants. If these data had been taken on the day following the weekly irrigations, then possibly a different pattern may have been found. The data in Figure 21, however, indicate that the leaves in the high-CO_2 chambers were definitely drier when sampled 5 or 6 days after each irrigation.

In conclusion, it appears that increased CO_2 concentration does not cause any significant shifts in the P-V curves relating leaf water potential to relative leaf water content. However, the increased CO_2 does alter where the plants are operating on the curves. The leaves of the plants from the higher CO_2 chambers were drier (lower RLWC and water potential), at least when sampled 5 or 6 days following an irrigation.

I. Pan Evaporation

Cumulative pan evaporation measurments were taken three days a week, May through September from all plots of the CO_2 experiment. Small cylindrical stainless steel pans (225 mm diameter X 110 mm high) were placed at the north end of the east walkway in each chamber and open field plot. An identical stainless steel pan was placed outside the NE corner of the experimental area over bare soil and adjacent to a standard U. S. Weather Bureau Class A pan (1210 mm diameter X 250 mm high). All the small pans were placed on concrete blocks (193 mm tall), while the Class A pan was on a wooden pallet. The pans were placed on these blocks to keep the pan water surface area above any shade created by the cotton canopy. As the cotton started to grow above the pan surface area, 2 additional concrete blocks were added on day of year 203 (22 July) and

another on day 219 (7 August) to keep the pans above the cotton canopy. The water depths were measured from all pans using a standard Lory type C hook gauge (0.1 mm accuracy). On day 165, algae was noticed growing in the evaporation pans. Rapid growth of the algae started to affect the evaporation rates of all the pans so an algacide,"ALL CLEAR" (trichloro-s-triazinetrione), was used thereafter to control the growth of the algae. All evaporation pans were cleaned and rinsed out every two weeks.

The cumulative evaporation for the Class A pan was 1753 mm and that for the small pan next to it was 2193 mm (Table 21, Figure 22). Thus, the larger surface to volume ratio of the small pan resulted in an evaporation rate that was 1.251 times larger than the Class A pan.

Early in the growing season (up to about day 170), the pans in all the experimental plots evaporated at very similiar rates while the cotton canopies were small (Figures 23, 24, 25, 26). As the season continued, there became a distinct difference in the chamber evaporation and the open field evaporation rates in the wet plots (Figures 23, 24). However, there was little difference between the chambers themselves at any level of CO_2 enrichment over the entire season.

The pan evaporation rates in the chambers of the dry plots were closer to those in the open field plots (Figures 25, 26) compared to the wet plots (Figures 23, 24). The closer approach to open-field pan evaporation could be due to the decreased humidity inside the dry chambers as opposed to the wet chambers.

The cumulative mean of all the dry plots was 1622 mm (Table 21) and that of the wet plots was 1492 mm, which means that the pan evaporation in the dry plots was 1.087 times as much as in the wet plots. Evidently most of this difference accumulated during the last half of the season when humidities were relatively lower in the dry plots as water stress closed stomates and reduced transpiration rates (Figures 23 - 26).

The mean of the open field plots (wet and dry) was 1668 mm (Table 21). The open field plots evaporated at a ratio of 1668/2193 or 0.761 times as much as the small standard pan next to the Class A pan. As mentioned previously, the evaporation rate from the small standard was 1.251 times that of the Class A, so therefore, the pan evaporation rate in the open field plots was 1.251 times 0.761 or 0.952 times as much as the Class A pan. There was no significant difference among the cumulative means of all the chambers due to CO_2 concentration (Table 21). Therefore, the "chamber effect" on pan evaporation was calculated taking the average of the means of all the chambers, 1549+1482+1528/3 (Table 21), divided by the mean of all the open field plots which is 1520 mm/1668 mm = 0.911. Thus the pan evaporation rate within the chambers averaged 8.9% less than that from the open field pans. Accounting for the pan size difference, for the outside to within the field difference, and for the "chamber effect", the evaporation rate from the small pans in the

chambers was 1.251 X 0.761 X 0.911 or 0.867 times as much as the Class A pan.

The amount of irrigation water applied to the well-watered or wet plots each week was based on the Class A pan evaporation rate (Equation 1). Therefore, since the adjusted pan evaporation inside the chambers was 13% less than the Class A pan amount, the irrigation amount should have been on the generous side.

J. Evolution of CO_2 from the Soil

Highly variable soil carbon dioxide flux values were obtained from inside the open-top chambers for the preceding years (Kimball et al., 1983, 1984). Furthermore, these values were consistently much lower than those obtained in the field outside the chambers. To find the cause of this behavior, further investigations were conducted in 1985. The study involved the determination of the carbon dioxide concentration in the soil profile within and outside the chambers. Specially fabricated hypodermic-type needles were inserted into the soil to depths of 5-, 10-, 20-, 40-, and 60-cm in the dry irrigation treatment. These were placed in the plant row, both inside and outside the chambers. Two mL of gas were extracted with syringes at weekly intervals from the various sites, and the carbon dioxide concentrations of the soil atmosphere samples were measured on an infrared gas analyzer.

Soil carbon dioxide concentrations as a function of sampling depth inside and outside the chambers are shown in Figures 27, 28 and 29 and cover additional experimental periods before and after the enrichment system was in operation. The blowers for the chambers were started on 02 May. Within two weeks of operation, soil carbon dioxide concentrations were distinctly higher outside than inside the chamber. In addition, the CO_2 concentration in the profile outside increased as the season progressed, reached a peak in August, and then started to decrease in October, in a manner similar to that reported by other investigators. In contrast, the CO_2 concentration of the soil within the chamber continued to decrease, particularly at the deepest 60 cm depth, and by September, the concentration at the 10 and 60 cm depths were nearly the same. When the blowers were turned off on 02 October, the concentration in the lower depths started to increase, and in approximately one month, the concentration profile was similar to that of soil outside the chamber.

Soil carbon dioxide fluxes from the open were higher than those taken inside the chamber during the period when the blower system was in operation (Figure 30). This difference in fluxes could be ascribed to the higher soil CO_2 concentration gradient for the open field compared to the chamber. Soil water contents inside and outside the chamber were nearly equivalent (Figure 31). Therefore, it is unlikely that differences in microbial respiration or in soil gas diffusion coefficient which are strongly influenced by soil water content would have contributed to the differences observed in soil carbon dioxide fluxes.

Air pressure on the chamber side of the blower was 125 pascal (1.25 mb, 0.5-inch of water) and could create an air pressure differential between inside and outside which could cause the unusually low soil CO_2 concentration within the chamber. Kanemasu et al. (1974) observed that the soil CO_2 flux measured with a "pressure"-type chamber was lower than that measured with a "suction" chamber. Pressure differentials relative to the atmosphere were +10 μbar and -24μbar, respectively, for their pressure and suction chambers. Our open-top system when the blower was in operation would most likely be similar to the pressure chamber of Kanemasu et al.

SUMMARY AND CONCLUSIONS

The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during the next century. To determine what effects this CO_2 increase is likely to have on the productivity, water relations, and physiological processes of field-grown cotton, the USDA-ARS U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory began CO_2 enrichment experiments on field-grown cotton in 1983 at Phoenix, Arizona. This report primarily presents the results of the 1985 experiment but also some summaries over the 3 years' data are included.

An open-top chamber approach was used. A manifold of perforated tubes released CO_2-enriched air at groundlevel between the plant rows. The enriched air rose through the plant canopy and exited through the chamber tops. Thus, the plants were subjected to radiation, temperature, and humidity conditions close to those of an open field but enriched with CO_2. A computer-controlled sampling/enrichment system was used to automatically monitor, control, and record CO_2 concentrations in the chambers. The nominal chamber CO_2 concentrations were ambient, 500, and 650 $\mu\ell\ \ell^{-1}$. The actual recorded overall means for the entire 1985 season were 367, 507, and 646 $\mu\ell\ \ell^{-1}$ and those for the daylight hours only were 349, 494, and 637 $\mu\ell\ \ell^{-1}$. Open field comparison plots were included, and their recorded CO_2 concentrations were very close to those in the ambient chambers.

There was a well-watered (wet) irrigation treatment and a water-stress (dry) treatment that received 2/3 as much water as the wet treatment. A drip irrigation system was installed in 1985, and it gave precise control of the water applications, much more so than the flood irrigation system used in 1984. Irrigations were done weekly with the amount of water applied to the wet plots being calculated from the Class A pan evaporation of the previous week times a leaf area index adjustment. Changes in soil moisture storage over the season were relatively small, so basically the amount of water used equalled the amount of water applied as irrigation and rainfall. The total water use averaged 1194 mm and 856 mm for the wet and dry treatments, respectively. There were two replicates for each irrigation-CO_2 treatment combination.

Significant findings from the experiment included the following:

1. For the wet plots, CO_2-enrichment increased seed cotton (lint + seed) yields by 45 and 52% at 500 and 650 $\mu\ell\ \ell^{-1}$, respectively. The corresponding total dry matter increases were 40 and 51%.

2. In the dry plots, seed cotton yields were increased by 64 and 104% and total dry matter by 52 and 71% at CO_2 concentrations of 500 and 650 $\mu\ell\ \ell^{-1}$, respectively. The greater CO_2-stimulation under water-stressed conditions is consistent with other literature reports but contrasts with our 1984 data. However, these 1985 data were obtained with more precise control of the irrigation treatments.

3. Aggregating all the yield data from 1983, 1984, and 1985, on the average a near-doubling of CO_2 concentration from 350 to 650 $\mu\ell\ \ell^{-1}$ increased seed cotton yields by 80%.

4. Seed index and harvest index were reduced by water stress but there was little influence of CO_2 enrichment on these traits.

5. The increased yield in 1985 from CO_2-enrichment can primarily be attributed to greater flower production. Boll retention percentages were affected very little by CO_2, consistent with our past years' data.

6. Leaf net photosynthesis rates were increased by 61 and 77% in the 500 and 650 $\mu\ell\ \ell^{-1}$ chambers, respectively, on the average for several days of sampling. This degree of photosynthetic stimulation by CO_2 was similar to the growth and yield stimulation.

7. Graphs of CO_2 assimilation rate of leaves from well-watered ambient and 650 $\mu\ell/\ell^{-1}$ CO_2 chambers plotted against intercellular CO_2 concentration were high and linear to at least 700 $\mu\ell/\ell^{-1}$. The linear dependence of photosynthesis on intercellular CO_2 concentration is uncommon in the literature.

8. Leaves from well-watered plants grown at 350 and 650 $\mu\ell/\ell^{-1}$ had the same photosynthetic response to changes in CO_2 concentration in July, which means there was no photosynthetic inhibition with acclimation to high CO_2. These last two findings together with a high stomatal conductance and relatively little change in conductance with increasing CO_2 may be the reasons that cotton has a larger growth response to CO_2 than most other species.

9. In contrast to finding 8, leaves from well-watered cotton plants acclimated to high CO_2 did show a photosynthetic inhibition in September. The primary difference in conditions between the two days was the cooler temperature in September than in July. Therefore, temperature dependent feedback effects are one possible explanation for differences in photosynthetic inhibition that have been reported in different studies.

10. The soluble carbohydrate (glucose, sucrose, fructose) content of the cotton leaves was affected very little by the CO_2 treatments. In marked contrast, the starch content increased by more than a factor of 5 in leaves from the 650 $\mu\ell\ \ell^{-1}$ chamber compared to those from the ambient chamber. There was a diurnal cycling of the starch content, but the amplitude of the cycle did not change much with CO_2 concentration but did decease with plant water stress. The early morning minimum was strongly affected by CO_2 concentration, suggesting that it was the lack of complete starch breakdown at night in the high CO_2 chamber that caused the high levels.

11. Leaf stomatal resistances were 47 and 69% higher on the average for several days at 650 $\mu\ell\ \ell^{-1}$ CO_2 compared to ambient in the wet and dry treatments, respectively.

12. A 300 to 600 $\mu\ell\ \ell^{-1}$ doubling of CO_2 concentration led to a foliage temperature increase of the well-watered cotton of about 0.9 C. The increased stomatal resistance at higher CO_2 (see previous findings) led to a per-unit-leaf-area reduction in transpiration of approximately 7.3%, which in turn caused the increased foliage temperature.

13. It appears that the degree of CO_2 stimulation of crop growth under well-watered conditions can be predicted from the magnitude of the foliage temperature increase in the higher CO_2. Using a foliage-temperature-based "stomatal closure index" corresponding to the 7.3% reduction in transpiration for cotton from a 300 to 600 $\mu\ell\ \ell^{-1}$ CO_2 concentration doubling, and using the results from prior experiments with water hyacinths which had an index of 0.178 and a growth stimulation of 35.6%, the cotton growth increase was predicted to be 35.6% X (0.178/0.073) = 86.2%, in excellent agreement with the average observed seed cotton yield increase of 80% due to a near-doubling of CO_2 concentration from 350 to 650 $\mu\ell\ \ell^{-1}$ (see finding no. 3).

14. Pressure-volume curves that relate leaf water potential to relative leaf water content were not significantly altered by CO_2 concentration. They were affected by the water stress treatment and by time of day.

15. Leaves sampled 5 or 6 days following an irrigation had progressively lower relative leaf water contents (and leaf water potentials) with increasing CO_2 concentration. Even though the P-V curves were not shifted by CO_2 (finding 14), the position on the curves where the plants operate in the field was changed. Evidently, the greater leaf area of the high-CO_2 plants caused them to transpire faster per unit of land area, more than compensating for their per-unit-leaf-area transpira-

tion reduction (finding 12), so that they in fact were drier 5 or 6 days following an irrigation.

16. The pan evaporation rate early in the season was the same within and outside the chambers. After full canopies were developed, the rates inside decreased below those outside, resulting in a season-long average reduction of 9%. The CO_2 treatments did not significantly affect the pan evaporation rates, but the rates in the dry plots were 9% higher on the average than those in the wet plots.

17. Soil CO_2 concentrations and soil surface CO_2 fluxes were much less in the chambers compared to outside after about a month of operation. The large difference apparently was related to the use of the blowers in the CO_2 enrichment system which caused the air pressure to be higher on the average inside the chambers than outside.

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* From the Western Cotton Research Laboratory

Table 1. Irrigation and rain amounts for the CO_2-cotton 85 experiment.

Date	Day of Year	Irrig. (I) or Rain (R)		Wet Plots Rep I	Wet Plots Rep II	Dry Plots Rep I	Dry Plots Rep II
				- - - - - - - - - -	- - - mm - - -	- - - - - - -	- - - - - - - -
15 Apr	105	I		50	49	47	53
20 Apr	110	R		1	1	1	1
22 Apr	112	I		24	37	36	32
24 Apr	114	I		24	26	23	26
25 Apr	115	I		21	22	22	23
28 Apr	118	R		3	3	3	3
24 May	144	I		18	20	10	10
31 May	151	I		25	25	17	14
7 Jun	158	I		13	12	7	7
11 Jun	162	I		7	8	6	5
14 Jun	165	I		34	24	21	17
21 Jun	172	I		65	48	36	35
28 Jun	179	I		64	68	46	47
5 Jul	186	I		86	84	57	57
12 Jul	192	I		93	85	50	51
15 Jul	196	R		23	23	23	23
18 Jul	199	R		5	5	5	5
19 Jul	200	I		40	57	27	23
26 Jul	207	I		73	72	49	44
2 Aug	214	I		90	91	64	70
9 Aug	221	I		67	72	42	36
16 Aug	228	I		64	72	43	44
20 Aug	232	R		21	21	21	21
23 Aug	235	I		38	50	26	25
30 Aug	242	I		74	79	57	52
31 Aug	243	R		6	6	6	6
6 Sep	249	I		108	69	67	74
13 Sep	256	I		24	54	8	3
18 Sep	261	R		17	17	17	17
19 Sep	262	R		1	1	1	1
20 Sep	263	I		36	38	18	16
26 Sep	269	R		5	5	5	5
27 Sep	270	R		1	1	1	1
			Totals	1221	1245	862	847

Table 2. Dates and amounts of N applied as urea throughout the drip irrigation system during the CO_2-cotton 85 experiment.

Date	Day of Year	Amount of N Applied kg/ha
11 June	162	16.6
14 June	165	16.6
21 June	172	11.1
28 June	179	16.6
5 July	186	16.6
12 July	193	16.6
19 July	200	16.6
26 July	207	16.6
2 August	214	16.6
8 August	221	16.6
16 August	228	11.1
23 August	235	11.1
	Total	182.7

Table 3. Petiole nitrate - N concentrations measured during the CO_2-cotton 85 experiment.

			Open Field		Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$)					
					Ambient		500		650	
Date	Day of Year	Rep:	I	II	I	II	I	II	I	II
DRY PLOTS:										
12 June	163		-	9.3	-	8.4	-	5.1	-	5.1
20 June	171		9.9	-	6.3	-	5.4	-	7.9	-
10,11 July	191,192		-	6.1	-	7.4	-	6.5	-	3.9
17,18 July	198,199		3.7	-	4.4	-	3.7	-	3.1	-
26,27 July	207,208		-	6.3	-	9.1	-	5.5	-	5.0
31 July, 1 Aug.	212,213		6.3	-	6.6	-	4.8	-	3.5	-
WET PLOTS:										
12 June	163		-	8.0	-	9.1	-	7.1	-	6.9
20 June	171		8.7	-	7.8	-	3.9	-	4.2	-
10,11 July	191,192		-	3.0	-	5.5	-	2.2	-	1.7
17,18 July	198,199		5.0	-	5.7	-	5.8	-	4.5	-
26,27 July	207,208		-	5.8	-	6.3	-	3.5	-	2.9
31 July, 1 Aug.	212,213		8.5	-	7.3	-	3.0	-	3.8	-

Table 4. Insecticide treatments applied during the CO_2-cotton 85 experiment.

DATE	DAY OF YEAR	INSECTICIDE	COMMENT	CHAMBER
Within Chambers and Open-field-plot Areas:				
3 May	123	Orthene	1/2 oz/gal, applied 2 gal.	All
5 June	156	Orthene	" "	All
21 June	172	Vapona	First time	All
25 June	176	Keltane		II W4 center row
28 June	179	Vapona	2nd time	All
1 July	182	Keltane		II W4 All rows
5 July	186	Vapona	3rd time	All
8 July	189	Keltane		IW4 & IIW4 All rows
9 July	190	Orthene		All
12 July	193	Vapona	4th time	All
		Thuricide	.5# in 3 gal water	All chambers & plots
19 July	200	Vapona		All
		Thuricide	.5# in 3 gal water	All chambers & plots
24 July	205	Keltane		IIW4 & IIW3 Spots
26 July	207	Vapona		All
29 July	210	Keltane		All
2 August	214	Vapona		All
5 August	217	Keltane		All
9 August	221	Vapona		All
12 August	224	Keltane		All
16 August	228	Vapona		All
19 August	231	Keltane		All
23 August	235	Vapona		All
27 August	239	Keltane		All
30 August	242	Vapona		All
6 Sept	249	Vapona		All
11 Sept	254	Keltane		All
13 Sept	256	Vapona		All
To Whole Field Outside Chambers:				
19 June	170	Guthion	2.31/ha	All plots outside chambers
27 June	178	Malathion	(0.85 l/ha)	" " " "
		Sevin	(2.24 kg/ha)	" " " "
		Keltane	(0.31 kg/ha)	" " " "
2 July	183	Malathion		" " " "
8 July	189	Malathion		" " " "
		Sevin		" " " "
		Keltane		" " " "
12 July	193	Cymbush	(0.39 kg/ha)	" " " "
26 July	207	Malathion		" " " "
29 August	241	Malathion		" " " "
8 Sept	251	Malathion		" " " "
15 Sept	258	Malathion		" " " "

Table 5. Total water use during the CO_2-cotton 1985 experiment as determined by the total amount of water applied through the drip irrigation system and adjusted for changes in soil moisture storage measured with neutron apparatus.

ITEM	OPEN FIELD Rep I	OPEN FIELD Rep II	CHAMBER CO_2 CONC. ($\mu\ell\ \ell^{-1}$) Ambient Rep I	Ambient Rep II	500 Rep I	500 Rep II	650 Rep I	650 Rep II
	mm							
WET PLOTS:								
"pre-irrigation" (15 Apr.)	50	49	50	49	50	49	50	49
17 Apr. soil water content	423	243	437	217	434	211	444	236
2 Oct. soil water content	431	226	433	202	437	188	432	213
Soil water content change	−8	+17	+4	+15	−3	+23	+12	+23
Irrigation + rain (20 Apr. - 27 Sep.)	1171	1196	1171	1196	1171	1196	1171	1196
Water use	1163	1213	1175	1211	1168	1219	1183	1219
average water use	1188		1193		1194		1201	
relative water use	0.996		1.000		1.001		1.007	
DRY PLOTS:								
"pre-irrigation" (15 Apr.)	47	53	47	53	47	53	47	53
17 Apr. soil water content	330	270	315	250	355	257	334	261
2 Oct. soil water content	286	224	269	204	280	213	274	215
	44	46	46	46	75	44	60	46
Irrigation + rain (20 Apr. - 27 Sep.)	815	794	815	794	815	794	815	794
Water use	859	840	861	840	890	838	875	840
average water use	850		851		864		858	
relative water use	0.999		1.000		1.015		1.008	

Table 6. Daytime, nighttime, and whole day mean CO_2 concentrations and the corresponding standard deviations of the individual observations for the entire season of the CO_2-cotton 85 experiment.

Condition		Open Field	NOMINAL CHAMBER CONC. Ambient	500	650
		$\mu\ell\ \ell^{-1}$			
Daytime:					
Wet	Rep I	344 ± 37	347 ± 38	497 ± 46	639 ± 77
	Rep II	346 ± 37	352 ± 42	490 ± 65	640 ± 70
Dry	Rep I	348 ± 39	353 ± 38	494 ± 59	628 ± 79
	Rep II	349 ± 38	342 ± 36	496 ± 61	640 ± 73
Nighttime:					
Wet	Rep I	376 ± 47	386 ± 51	513 ± 52	661 ± 85
	Rep II	380 ± 51	402 ± 66	533 ± 81	655 ± 78
Dry	Rep I	386 ± 54	388 ± 49	515 ± 64	655 ± 87
	Rep II	384 ± 52	374 ± 45	520 ± 82	655 ± 77
Whole (24 hr) Day:					
Wet	Rep I	359 ± 45	365 ± 49	504 ± 50	650 ± 82
	Rep II	362 ± 47	376 ± 60	511 ± 76	647 ± 75
Dry	Rep I	366 ± 51	370 ± 47	504 ± 62	641 ± 84
	Rep II	366 ± 48	357 ± 43	507 ± 73	647 ± 75
Overall Means Averaged Over Reps and Water Treatments:					
		363 ± 48	367 ± 51	507 ± 66	646 ± 79

Table 7. Seed cotton yield, total dry matter production, and other yield data for the CO_2-cotton 1985 experiment.

Item	OPEN FIELD				CO_2 Concentration in Chambers (μℓ/ℓ) AMBIENT				500				650			
	W		D		W		D		W		D		W		D	
	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
Plants/m^2	8.3	8.3	9.0	10.0	9.0	8.3	8.0	10.0	8.7	10.3	9.7	9.3	8.7	7.3	8.3	9.3
Plant Height (mm)	66.98	67.90	56.55	56.19	76.76	78.24	66.57	63.55	78.81	89.83	69.05	65.86	77.94	87.41	67.76	72.42
No. Bolls/m^2	119	103	97	95	131	121	70	75	206	176	103	115	197	182	141	126
Plant Top Dry Wt. (g/m^2)	829	840	737	746	1068	1163	643	649	1571	1551	953	1009	1664	1681	1064	1158
Root Dry Wt. (g/m^2)	57	54	61	59	82	98	96	88	119	137	146	134	148	154	144	157
Total	886	894	798	805	1150	1261	739	737	1690	1688	1099	1143	1812	1835	1208	1315
Average	890		802		1205		738		1689		1121		1821		1262	
Rel. CO_2 Effect	0.74		1.09		1.00		1.00		1.40		1.52		1.51		1.71	
Lint Weight (g/m^2)	132	137	108	119	162	163	64	69	265	213	108	112	251	254	151	123
Seed Weight (g/m^2)	239	244	178	194	286	287	116	120	448	380	191	196	440	423	253	226
% Lint	36	36	38	38	36	36	36	37	37	36	36	36	36	38	37	35
Seed Cotton Wt. (g/m^2)	371	381	286	313	448	450	180	189	713	593	299	308	691	677	404	349
Avg. Seed Cotton	376		300		449		185		653		304		684		377	
Rel. CO_2 Effect	0.837		1.62		1.00		1.00		1.45		1.64		1.52		2.04	
Avg. Lint Wt.	135		114		163		67		239		110		253		137	
Rel. CO_2 Effect	0.828		1.70		1.00		1.00		1.47		1.64		1.55		2.04	
Seed Index (g/100 seeds)	10.9	10.1	9.5	9.2	9.5	10.9	8.7	8.9	11.1	10.7	9.0	9.1	10.9	10.5	9.9	9.7
Harvest Index (%) (seed cotton wt./plant top wt.)	44	45	39	42	42	39	28	29	45	38	31	31	42	40	38	30
Average	45		40		40		29		42		31		41		34	

Table 8. Number of flowers tagged per m^2 in 1985.

Plot No.	Open Field	Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$) Ambient	500	650
I W	142	212	314	364
II W	142	251	300	394
Avg. Wet	142	231	307	379
I D	146	176	303	334
II D	133	187	315	403
Avg. Dry	139	181	309	369

Table 9. Number of tagged flowers retained as bolls per m^2 in 1985.

Plot No.	Open Field	Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$) Ambient	500	650
I W	61	86	128	142
II W	61	82	117	137
Avg. Wet	61	84	123	140
I D	54	41	63	83
II D	50	53	73	80
Avg. Dry	52	47	68	82

Table 10. Percentage of tagged flowers retained as mature bolls in 1985.

	Open Field	Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$) Ambient	500	650
	%	%	%	%
I W	43.2	40.6	40.8	39.1
II W	42.8	32.7	39.1	34.7
Avg. Wet	43.0	36.6	40.0	36.9
I D	37.1	23.5	20.3	24.9
II D	37.6	28.2	23.0	19.9
Avg. Dry	37.4	25.8	21.6	22.4

Table 11. Boll retention in 1985 by week for the Wet - Replicate I plots where A and R are number of applied and retained tags, respectively, per m^2.

Days of Year Inclusive	Open Field			Chamber CO_2 Conc. ($\mu\ell/\ell$) AMB			500			650		
	A	R	%	A	R	%	A	R	%	A	R	%
161-165	0.7	0.7	100	2.3	0.7	28.6	0.0	0.0	-	5.3	2.0	37.5
168-172	5.3	4.7	87.5	16.3	4.7	28.6	12.0	6.0	50.0	25.0	7.0	28.0
175-179	15.3	9.7	63	30.7	16.7	54.3	38.3	22.3	58.3	53.7	27.0	50.3
182-186	25.3	11.0	43.4	21.3	2.3	10.9	48.3	7.0	14.5	47.0	4.0	8.5
190-193	27.3	10.3	37.8	14.3	2.7	18.6	27.7	8.7	31.3	18.3	4.0	21.8
196-200	27.7	10.7	38.6	27.7	10.7	38.6	45.0	13.7	30.4	43.7	16.7	38.2
203-207	12.7	4.3	34.2	13.7	8.7	63.4	27.0	10.0	37.0	30.0	13.6	45.6
210-214	8.3	4.0	48.0	29.0	20.0	69.0	43.0	28.7	66.7	53.3	36.3	68.1
217-221	6.7	2.7	40.0	30.3	15.7	51.6	40.7	18.7	45.9	53.0	27.7	52.2
224-228	1.3	0.0	0.0	16.7	2.3	14.0	16.7	7.0	42.0	20.7	3.7	17.7
231-235	2.0	1.3	66.7	5.0	1.0	20.0	8.3	3.7	44.0	10.7	0.3	3.1
238-242	9.3	2.0	21.4	4.3	0.7	15.4	7.0	2.3	33.3	10.0	0.0	0.0
TOTAL	142.0	61.3	43.2	211.7	86.0	40.6	314.0	128.0	40.8	364.0	142.3	39.1

Table 12. Boll retention in 1985 by week for the Wet - Replicate II plots where A and R are number of applied and retained tags, respectively, per m^2.

Days of Year Inclusive	Open Field			Chamber CO_2 Conc. ($\mu\ell/\ell$) AMB			500			650		
	A	R	%	A	R	%	A	R	%	A	R	%
161–165	3.0	2.0	66.7	1.7	0.0	0.0	4.0	2.0	50.0	4.0	1.0	25.0
168–172	9.3	6.0	64.3	12.7	3.7	28.9	25.3	7.7	30.3	20.0	4.3	21.7
175–179	27.0	20.0	74.1	23.3	8.3	35.7	40.7	13.3	32.8	47.7	12.7	26.6
182–186	24.3	5.7	23.3	21.3	0.3	1.6	39.3	4.7	11.9	51.7	4.0	7.7
190–193	8.3	2.7	32.0	11.0	2.3	21.2	16.3	4.0	24.5	21.3	4.0	18.8
196–200	12.3	3.3	27.0	25.0	4.3	17.3	37.7	13.0	34.5	43.0	16.0	37.2
203–207	3.3	1.0	30.0	25.0	6.3	25.3	37.3	21.6	58.0	47.7	23.7	49.7
210–214	8.3	5.7	68.0	37.0	30.7	82.4	35.0	22.3	63.8	65.0	41.7	64.1
217–221	16.7	8.3	50.0	40.0	16.0	40.0	38.0	17.7	46.5	43.0	16.3	38.0
224–228	7.0	1.3	19.0	32.3	6.0	18.6	19.0	8.3	43.9	29.0	8.7	30.0
231–235	13.3	2.7	20.0	19.7	3.3	16.9	4.7	1.3	28.6	18.3	4.7	25.5
238–242	8.7	2.0	23.1	2.0	0.7	33.3	3.0	1.3	44.4	3.2	0.0	0.0
TOTAL	141.7	60.7	42.8	251.0	82.0	32.7	300.3	117.3	39.1	394.3	137.0	34.7

Table 13. Boll retention in 1985 by week for the Dry - Replicate I plots where A and R are number of applied and retained tags, respectively, per m^2.

Days of Year Inclusive	Open Field			Chamber CO_2 Conc. ($\mu\ell/\ell$) AMB			500			650		
	A	R	%	A	R	%	A	R	%	A	R	%
161–165	1.3	0.7	50.0	2.7	1.0	37.5	4.0	1.0	25.0	3.7	1.3	36.4
168–172	6.3	4.0	63.2	11.0	2.3	21.2	29.0	3.0	10.3	19.7	4.7	23.7
175–179	19.7	12.3	62.7	18.0	3.0	16.7	42.7	3.0	7.0	44.3	7.3	16.5
182–186	22.3	5.0	22.4	10.3	0.3	3.2	17.7	0.3	1.9	31.3	1.7	5.3
190–193	13.7	5.0	36.6	8.7	0.0	0.0	19.3	0.3	1.7	14.7	2.0	13.6
196–200	13.3	7.3	55.0	13.3	2.7	20.0	27.7	1.7	6.0	29.0	3.0	10.3
203–207	8.0	1.3	16.7	17.0	1.3	7.8	36.7	5.3	14.5	36.7	3.0	8.2
210–214	8.0	3.7	45.8	28.7	19.3	67.4	52.7	30.7	58.2	57.0	37.3	65.5
217–221	6.7	5.7	85.0	42.7	9.7	22.7	38.3	15.0	39.1	57.3	16.3	28.5
224–228	7.3	1.7	22.7	20.0	1.0	5.0	28.3	1.3	4.7	27.3	2.0	7.3
231–235	15.3	4.7	30.4	3.0	0.7	22.2	5.7	1.7	29.4	11.0	4.3	39.4
238–242	23.7	2.7	11.3	0.3	0.0	0.0	1.3	0.0	0.0	2.3	0.3	14.3
TOTAL	145.7	54.0	37.1	175.7	41.3	23.5	303.3	63.3	20.3	334.3	83.3	24.9

Table 14. Boll retention in 1985 by week for the Dry - Replicate II plots where A and R are number of applied and retained tags, respectively, per m^2.

				Chamber CO_2 Conc. ($\mu\ell/\ell$)								
	Open Field			AMB			500			650		
Days of Year Inclusive	A	R	%	A	R	%	A	R	%	A	R	%
161–165	2.3	1.3	57.1	2.0	0.7	33.3	3.3	0.7	20.0	5.3	1.7	31.2
168–172	8.7	4.7	53.8	11.0	2.3	21.2	20.7	2.0	9.7	29.0	2.7	9.2
175–179	27.3	15.0	54.9	20.7	2.7	12.9	40.0	6.0	15.0	45.7	4.0	8.8
182–186	21.0	2.3	11.1	16.0	0.7	4.2	21.3	1.3	6.2	30.0	0.3	1.1
190–193	8.0	1.3	16.7	8.3	1.0	12.0	16.0	0.7	4.2	19.7	0.0	0.0
196–200	5.7	3.3	58.8	17.3	1.7	9.6	26.7	1.7	6.2	39.3	5.7	14.4
203–207	3.0	1.3	44.4	16.3	1.7	10.2	35.7	3.3	9.3	56.0	5.7	10.1
210–214	6.3	4.1	68.4	36.0	20.7	57.4	58.3	31.7	54.3	72.7	40.0	55.0
217–221	21.0	13.7	65.1	37.7	16.3	43.4	52.0	18.3	35.3	62.0	15.0	24.2
224–228	6.7	1.0	15.0	16.3	2.7	16.3	29.0	4.7	16.1	29.7	3.0	10.1
231–235	13.3	1.7	12.5	5.0	2.3	46.7	10.0	2.3	23.3	11.0	2.3	21.2
238–242	9.7	0.0	0.0	0.3	0.0	–	2.3	0.0	0.0	2.7	0.0	0.0
TOTAL	133.0	50.0	37.6	187.0	52.7	28.2	315.3	72.7	23.0	403.0	80.3	19.9

Table 15. Mean net leaf photosynthetic rates during the CO_2-cotton 85 experiment. Means not followed by the same letter are significantly different at the 0.05 probability level within each treatment category. The number of observations within each irrigation - CO_2 treatment combination was 69. The numbers in parentheses are the relative increases with respect to the ambient CO_2 chamber.

	CO_2 Treatment				
		Chamber CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
Irrigation	Open Field	Ambient	500	650	Mean
	μ mole $m^{-2}\ s^{-1}$				
Wet	21.6 (0.89)	24.3 (1.00)	38.3 (1.58)	42.8 (1.76)	31.8 B
Dry	20.6 (0.97)	21.3 (1.00)	34.8 (1.63)	38.0 (1.78)	28.6 A
Mean	21.1a (0.93)	22.8 a (1.00)	36.6 b (1.61)	40.4 c (1.77)	

Table 16. Characteristics of photosynthesis on 3-4 July 1985.

	Chamber or Growth CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
	650		350 (or Ambient)	
Item [a]	Wet	Dry	Wet	Dry
A_{max} (μmol $m^{-2}s^{-1}$)	51	35	51	39
c_i for A_{max} ($\mu\ell/\ell$)	980	760	980	800
c_e for A_{max} (")	1080 [b]	920 [b]	1070 [b]	910 [b]
A at 650 $\mu\ell/\ell$ (μmol $m^{-2}s^{-1}$)	42	30	43 [b]	35 [b]
A at 350 $\mu\ell/\ell$ (")	24 [b]	16 [b]	24	21
(A at 650)/(A at 350)[d]	1.75	1.43	-	-
Operating c_i ($\mu\ell/\ell$)	560	510	300	290
g_m' (for CO_2) (cm/s)	0.36	0.35	0.36	0.35
g_s (for H_2O) (")	1.95 [e]	0.84 [e]	2.11 [e]	1.44 [e]
Γ ($\mu\ell/\ell$)	75	105	75	85
Photoresp. (μmol $m^{-2}s^{-1}$)	9 [c]	12 [c]	9 [c]	10 [c]

[a] A_{max} is the maximum observed assimilation rate, c_i is the CO_2 concentration in the substomatal cavities, c_e is the external CO_2 concentration g_m' is the mesophyll conductance for CO_2, g_s is the stomatal conductance for water vapor, and Γ is the CO_2 compensation point or concentration where A = 0.

[b] These numbers are not rigorous. Strictly speaking, the data cannot be used to calculate assimilation rate at any given c_e except at the c_e in which the plants were grown. This is because measurements were completed before stomata had a chance to react to altered c_e. Thus only at the original c_e would stomatal limitations to photosynthesis be the same as the long-term value. However, one can assume unchanging stomatal conductance in response to CO_2 and make crude calculations. These are what is presented here. The assumption seems quite reasonable for the wet treatments.

[c] Determined as A at c_i = 0 by extrapolation. Thus it actually is a measure of photorespiration at very low c_i, not at the actual c_i experienced by the plants under normal conditions. As a result, it overestimates actual photorespiration, but still is useful for comparisons among treatments.

[d] A at 650 $\mu\ell\ \ell^{-1}$ CO_2 from plants grown at 650 $\mu\ell\ \ell^{-1}$ divided by A at 350 $\mu\ell\ \ell^{-1}$ from plants grown at 350 $\mu\ell\ \ell^{-1}$ (ambient).

[e] To convert to g'_s (for CO_2) divide by 1.6. The values can then be compared directly to g'_m. Note that some of these values predict very large stomatal limitations to photosynthesis. In those cases (e.g., the dry treatments on 17 Sept.) the calculations of c_i, etc., are error-prone and should be considered somewhat unreliable.

Table 17. Characteristics of photosynthesis on 28 August 1985.

Item [a]	Chamber or Growth CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
	650		350 (or Ambient)	
	Wet	Dry	Wet	Dry
A_{max} (μmol $m^{-2}s^{-1}$)	45	16	45	16
c_i for A_{max} ($\mu\ell/\ell$)	710	620	710	620
c_e for A_{max} (")	790 [b]	932 [b]	800 [b]	800 [b]
A at 650 $\mu\ell/\ell$ (μmol $m^{-2}s^{-1}$)	43	13	43 [b]	15 [b]
A at 350 $\mu\ell/\ell$ (")	26 [b]	6 [b]	26	8
(A at 650)/(A at 350)[d]	1.65	1.63	-	-
Operating c_i ($\mu\ell/\ell$)	570	400	300	260
g_m' (for CO_2) (cm/s)	0.45	0.24	0.45	0.24
g_s (for H_2O) (")	2.07 [e]	0.20 [e]	2.00 [e]	0.34 [e]
Γ ($\mu\ell/\ell$)	70	110	70	110
Photoresp. (μmol $m^{-2}s^{-1}$)	10 [c]	9 [c]	10 [c]	9 [c]

[a] See Table 16.

[b] See Table 16.

[c] See Table 16.

[d] See Table 16.

[e] See Table 16.

Table 18. Characteristics of photosynthesis on 17 September 1985.

Item [a]	Chamber or Growth CO_2 Conc. ($\mu\ell\ \ell^{-1}$)			
	650		350 (or Ambient)	
	Wet	Dry	Wet	Dry
A_{max} (μmol $m^{-2}s^{-1}$)	44	36	45	40
c_i for A_{max} ($\mu\ell/\ell$)	840	440	520	720
c_e for A_{max} (")	1240 [b]	1720 [b]	820 [b]	1280 [b]
A at 650 $\mu\ell/\ell$ (μmol $m^{-2}s^{-1}$)	26	13	41 [b]	23 [b]
A at 350 $\mu\ell/\ell$ (")	12 [b]	6 [b]	21	10
(A at 650)/(A at 350)[d]	1.24	1.30	-	-
Operating c_i ($\mu\ell/\ell$)	420	170	200	210
g_m' (for CO_2) (cm/s)	0.31	0.54	0.54	0.38
g_s (for H_2O) (")	0.43 [e]	0.11 [e]	0.58 [e]	0.28 [e]
Γ ($\mu\ell/\ell$)	110	100	80	120
Photoresp. (μmol $m^{-2}s^{-1}$)	11 [c]	16 [c]	14 [c]	13 [c]

[a] See Table 16.

[b] See Table 16.

[c] See Table 16.

[d] See Table 16.

[e] See Table 16.

Table 19. Carbohydrate content of cotton leaves at the beginning and end of a day.

Sample Time	Chamber CO_2 $\mu\ell\ \ell^{-1}$	Glucose	Sucrose	Fructose	Starch	Starch, Daily Change
		---- mg Glucose equiv./dm^2 -----				
DRY PLOTS:						
6:30 AM	Ambient	14.4	8.4	0.0	8.4	23.2
7:00 PM	Ambient	14.3	17.3	0.0	31.6	
6:30 AM	500	16.3	13.7	0.0	49.5	38.8
7:00 PM	500	15.6	20.4	0.0	88.3	
6:30 AM	650	17.4	12.5	0.3	68.9	29.6
7:00 PM	650	15.4	19.4	0.0	98.5	
WET PLOTS:						
6:30 AM	Ambient	16.0	18.5	0.0	22.3	73.9
7:00 PM	Ambient	15.2	22.9	0.0	96.2	
6:30 AM	500	15.5	8.2	0.0	43.2	70.4
7:00 PM	500	14.1	21.8	0.7	113.6	
6:30 AM	650	17.8	6.7	0.0	115.9	46.4
7:00 PM	650	18.5	8.5	0.0	162.4	

Table 20. Mean stomatal resistances and their corresponding standard deviations during the CO_2 - cotton 85 experiment. Means not followed by the same letter are significantly different at the 0.05 probability level within each irrigation category.

IRRIGATION	NO. OBS.		OPEN FIELD	CHAMBER AMBIENT	CO_2 CONC. ($\mu\ell\ \ell^{-1}$) 500	650
			$s\ m^{-1}$			
Including all days for which data was obtained:						
Dry	39	Mean	68.6 a	72.7 a	95.8 ab	122.7 b
		S.D.	10.6	11.9	17.5	26.7
Wet	39	Mean	50.1 c	30.8 a	38.3 ab	45.2 bc
		S.D.	4.5	2.8	4.1	6.9
Including only data within 4 days of an irrigation:						
Wet	27	Mean	34.9 c	22.4 a	27.2 ab	29.1 bc
		S.D.	2.3	1.6	1.9	3.8

Table 21. Cumulative Pan Evaporation During the CO_2-cotton 85 Experiment.

Class A : 1753 mm
Small Standard : 2193 mm

Irrigation	Rep	Open Field	CO_2 Conc. in Chambers ($\mu\ell/\ell$) Amb. Chm.	500	650	means[1]
		mm				
Wet	I	1654	1432	1390	1454	1492A
Wet	II	1637	1501	1448	1422	
Dry	I	1692	1605	1527	1663	1622B
Dry	II	1690	1661	1564	1574	
	means[1]:	1668a	1549b	1482b	1528b	

[1] Means not followed by the same letter are significantly different at a 0.05 confidence level using Student-Newman-Keuls test.

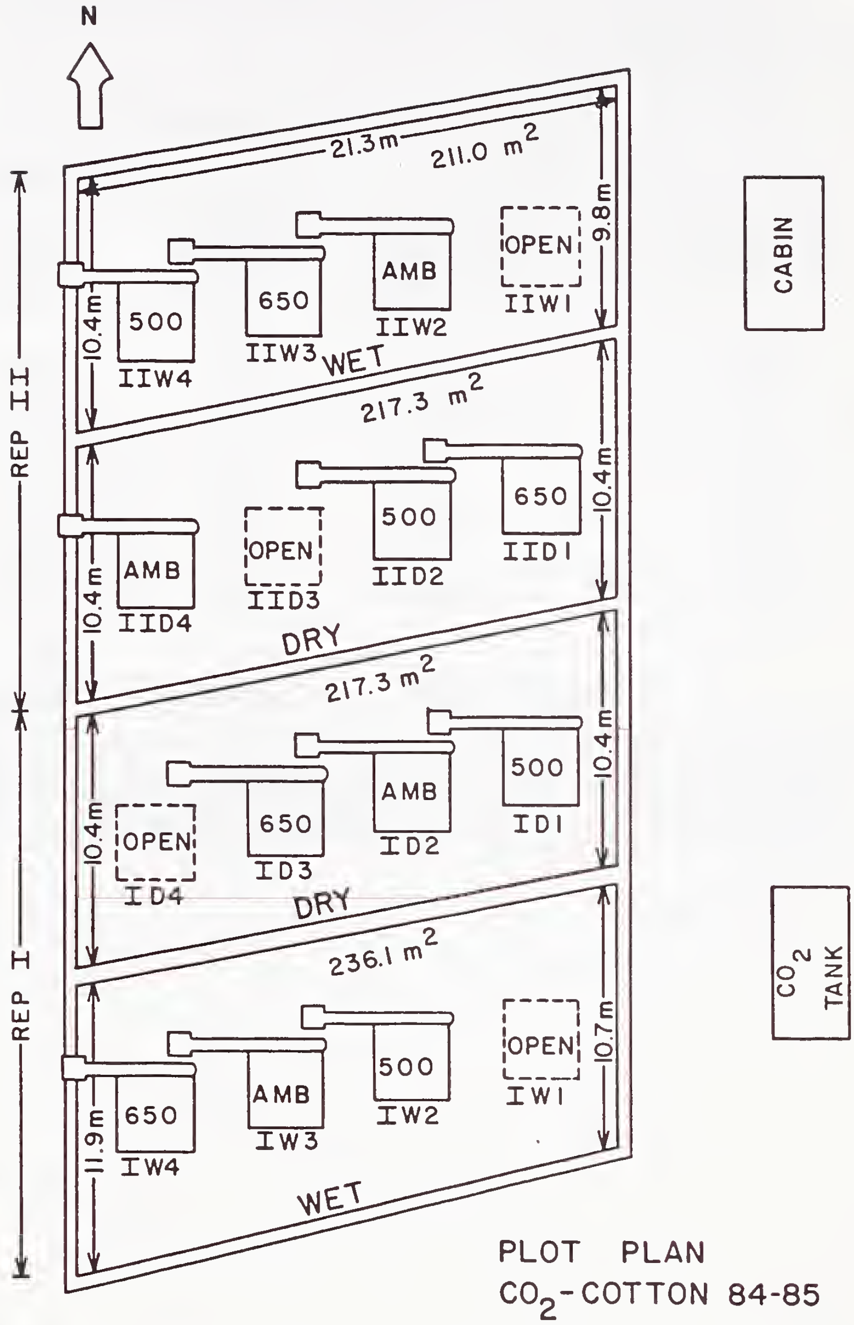

Figure 1. Plot plan for the CO_2-cotton experiments in 1984 and 1985.

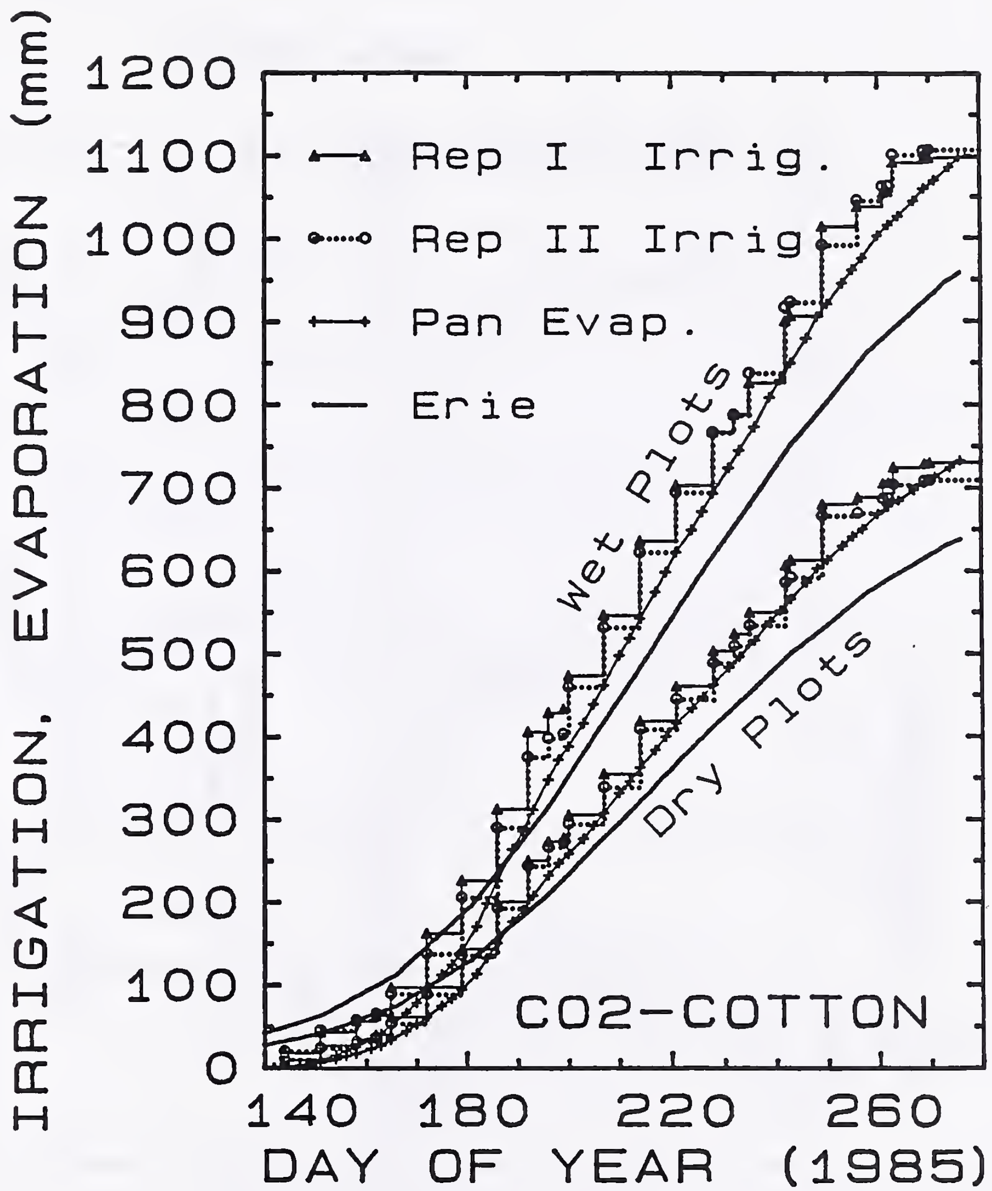

Figure 2. Amounts of irrigation and rainfall applied to the wet and dry plots versus day of year for the CO_2-cotton 85 experiment. The initial irrigations applied in April before differential irrigations began are not included. Also plotted are the measured pan evaporation (X LAI/3) and the Erie et al. (1981) consumptive use curve for cotton for comparison with the wet plots as well as 2/3 of these amounts for comparison with the dry plots.

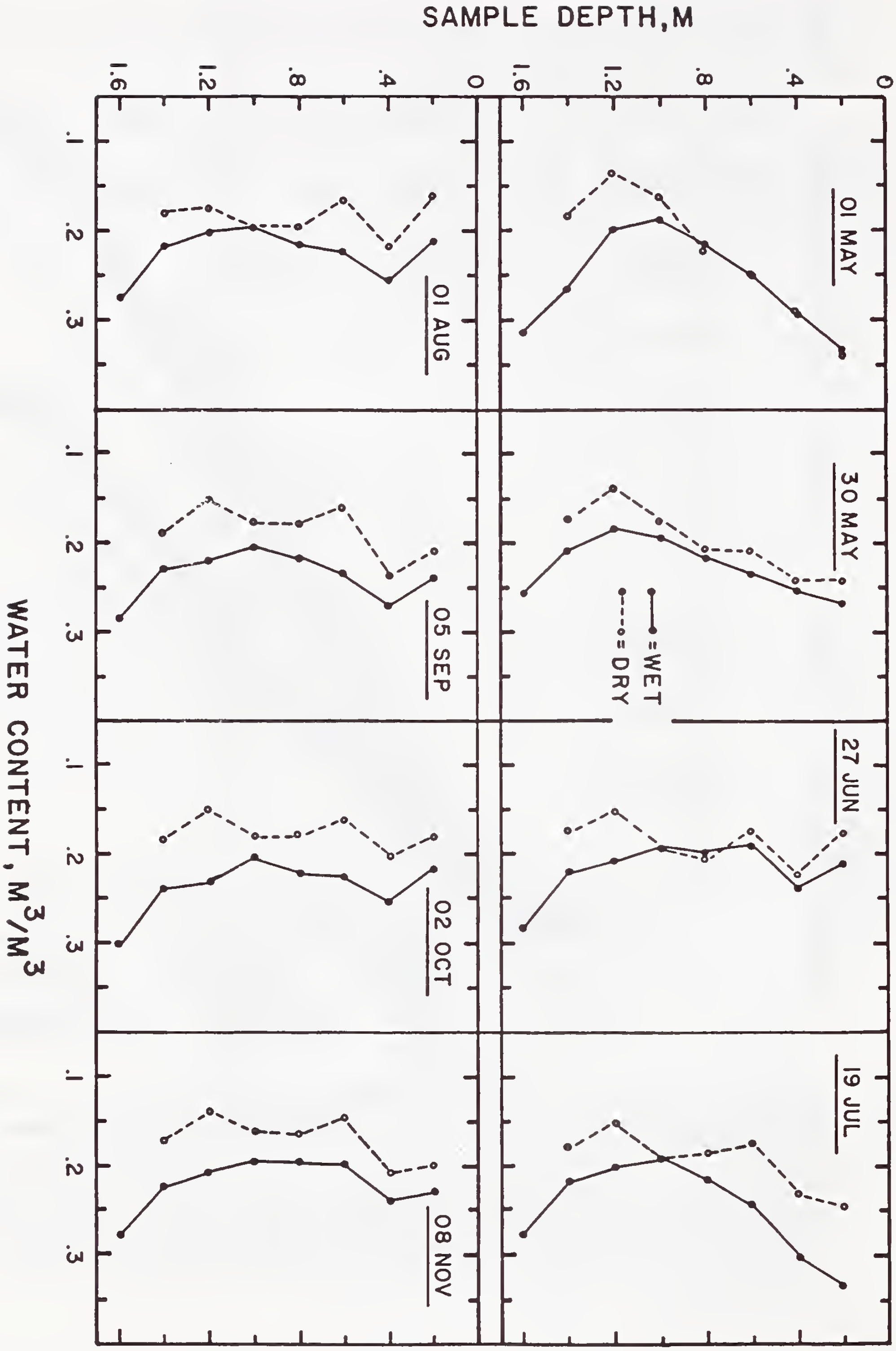

Figure 3. Profiles of volumetric soil water content against soil depth from neutron apparatus for all ambient CO_2 chambers and open-field plots. The "wet" data are averages of the wet, 350 $\mu\ell\ \ell^{-1}$ CO_2 plots (IW1, IW3, IIW1, and IIW2) and the "dry" data are averages of the dry, 350 $\mu\ell\ \ell^{-1}$ CO_2 plots (ID2, ID4, IID3, and IID4).

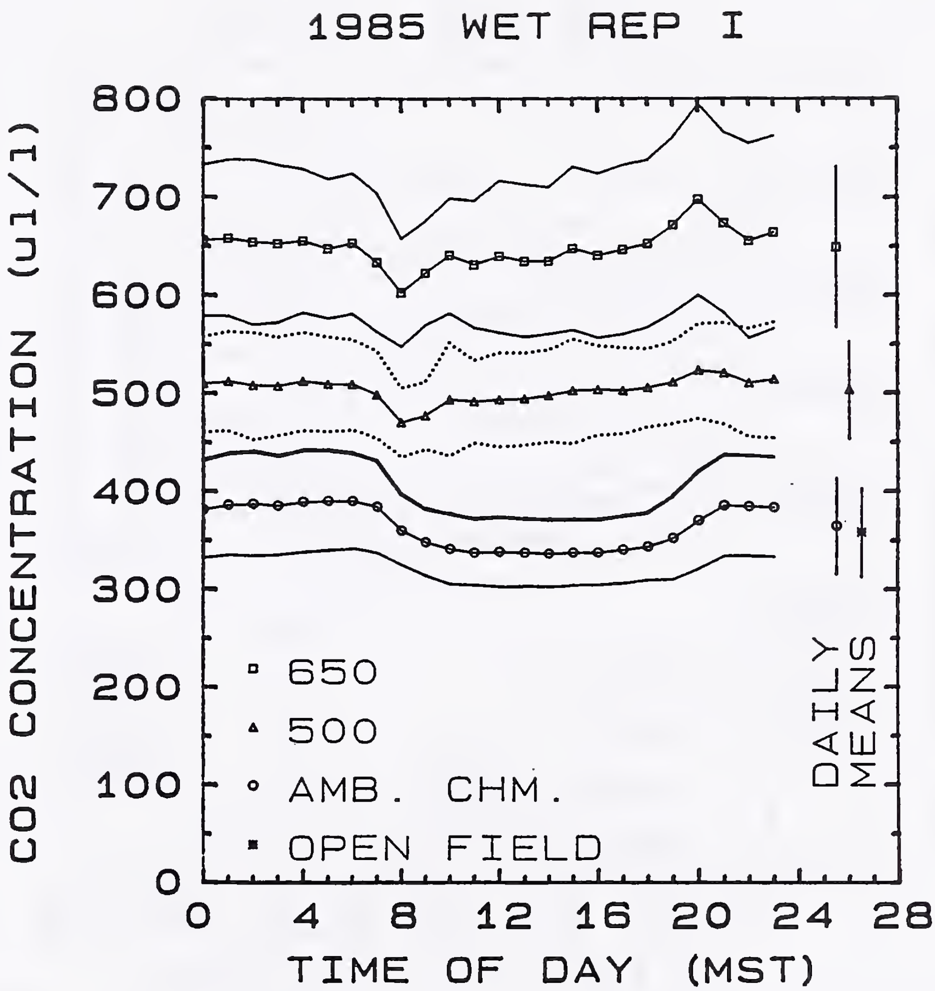

Figure 4. Diurnal pattern of mean CO_2 concentration for the Rep I-wet chambers in 1985. The upper and lower pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the three chambers and the open field plot.

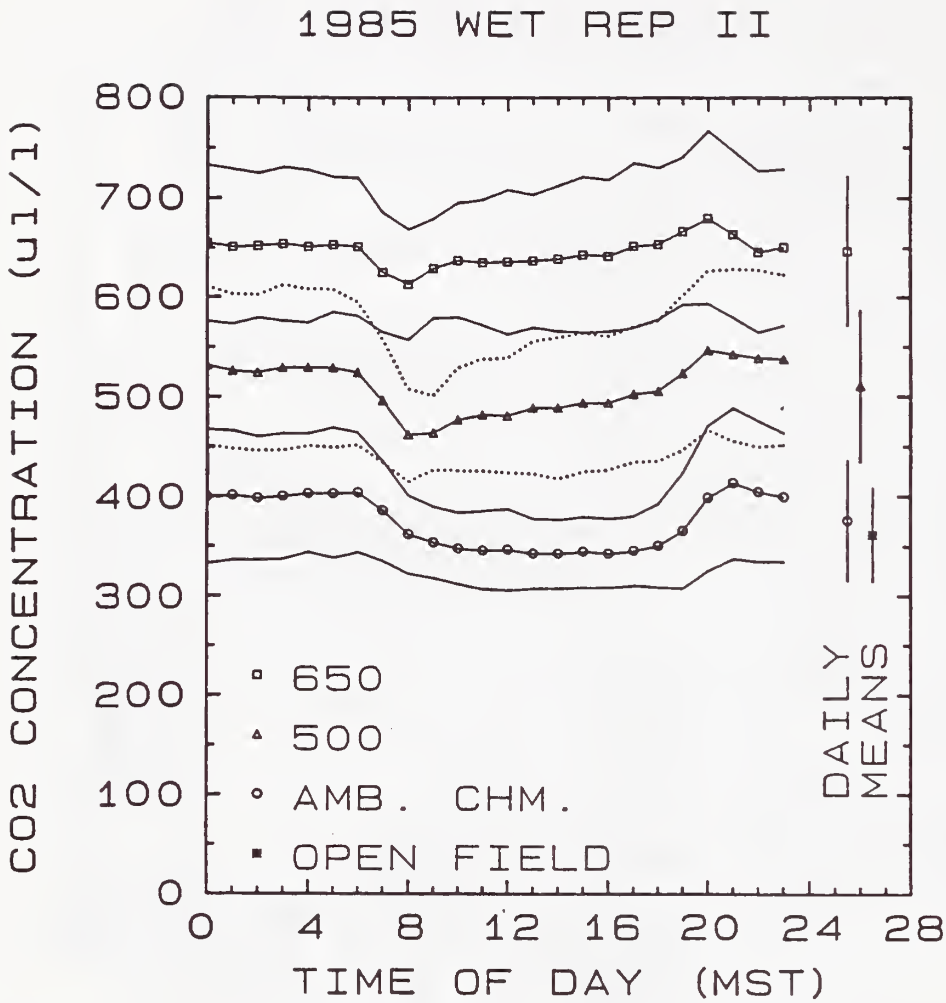

Figure 5. Diurnal pattern of mean CO_2 concentration for the Rep II-wet chambers in 1985. The upper and lower pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the three chambers and the open field plot.

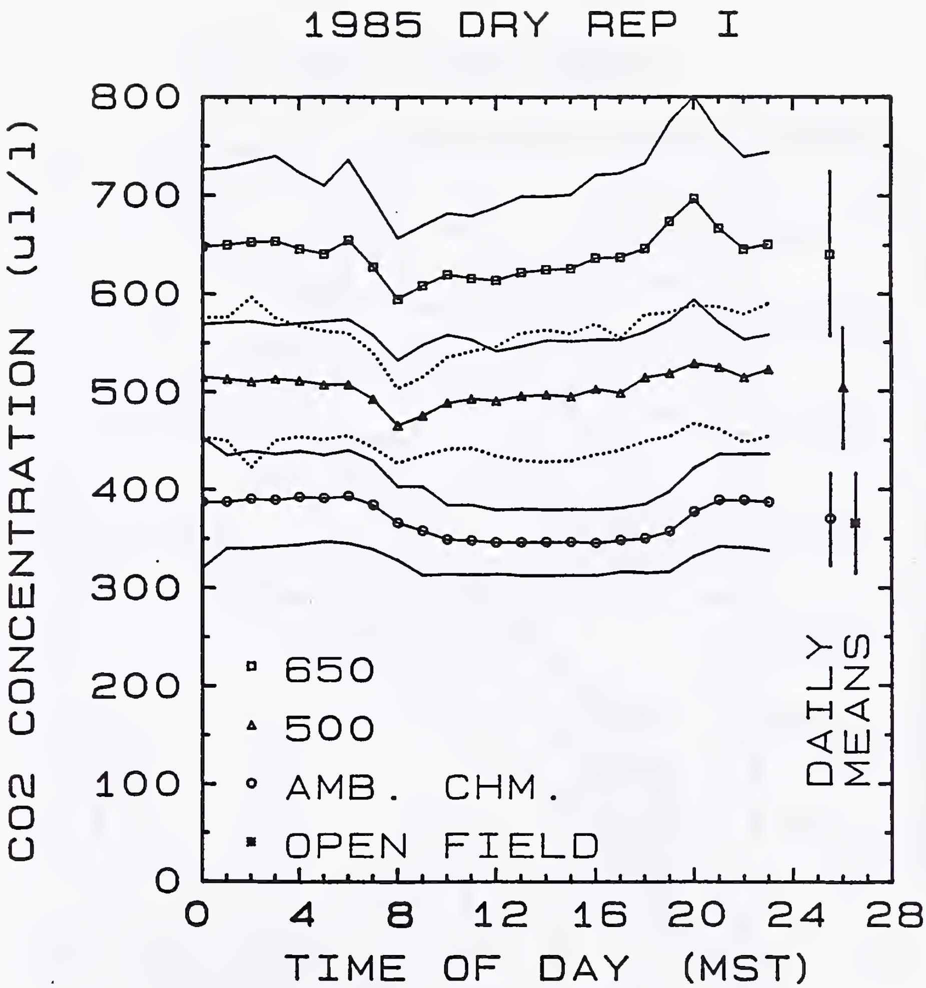

Figure 6. Diurnal pattern of mean CO_2 concentration for the Rep I-dry chambers in 1985. The upper and lower pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the three chambers and the open field plot.

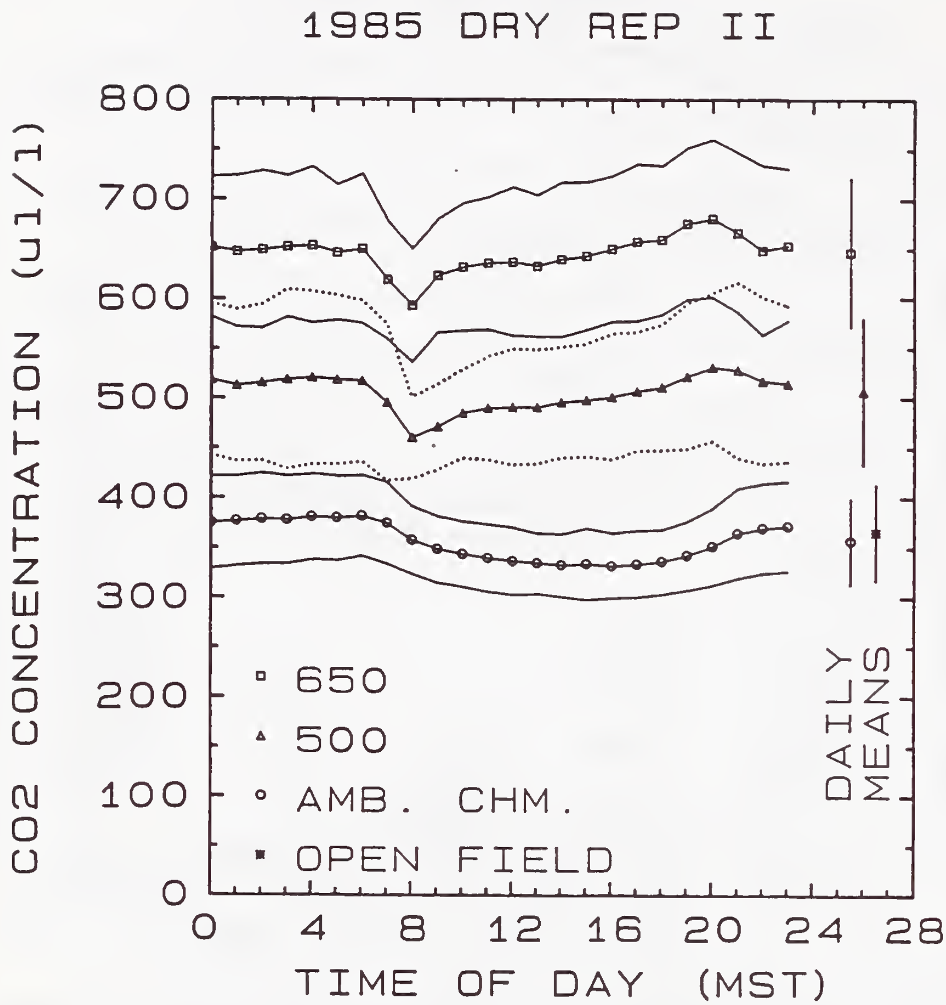

Figure 7. Diurnal pattern of mean CO_2 concentration for the Rep II-dry chambers in 1985. The upper and lower pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the three chambers and the open field plot.

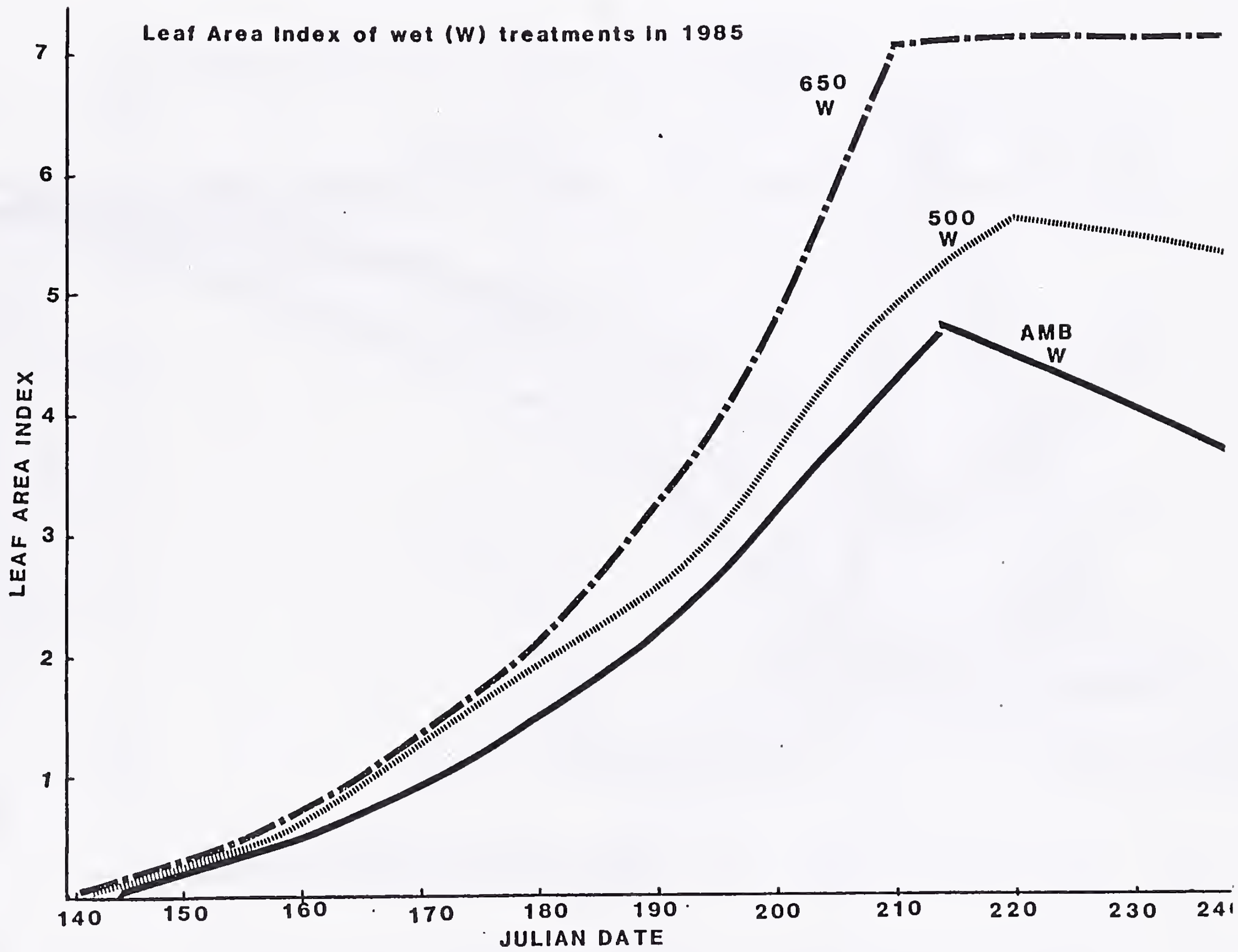

Figure 8. Leaf area index of the plants in the wet ambient, 500, and 650 µℓ ℓ^{-1} CO_2 chambers for the CO_2-cotton 85 experiment. The data are the average of the two replicates.

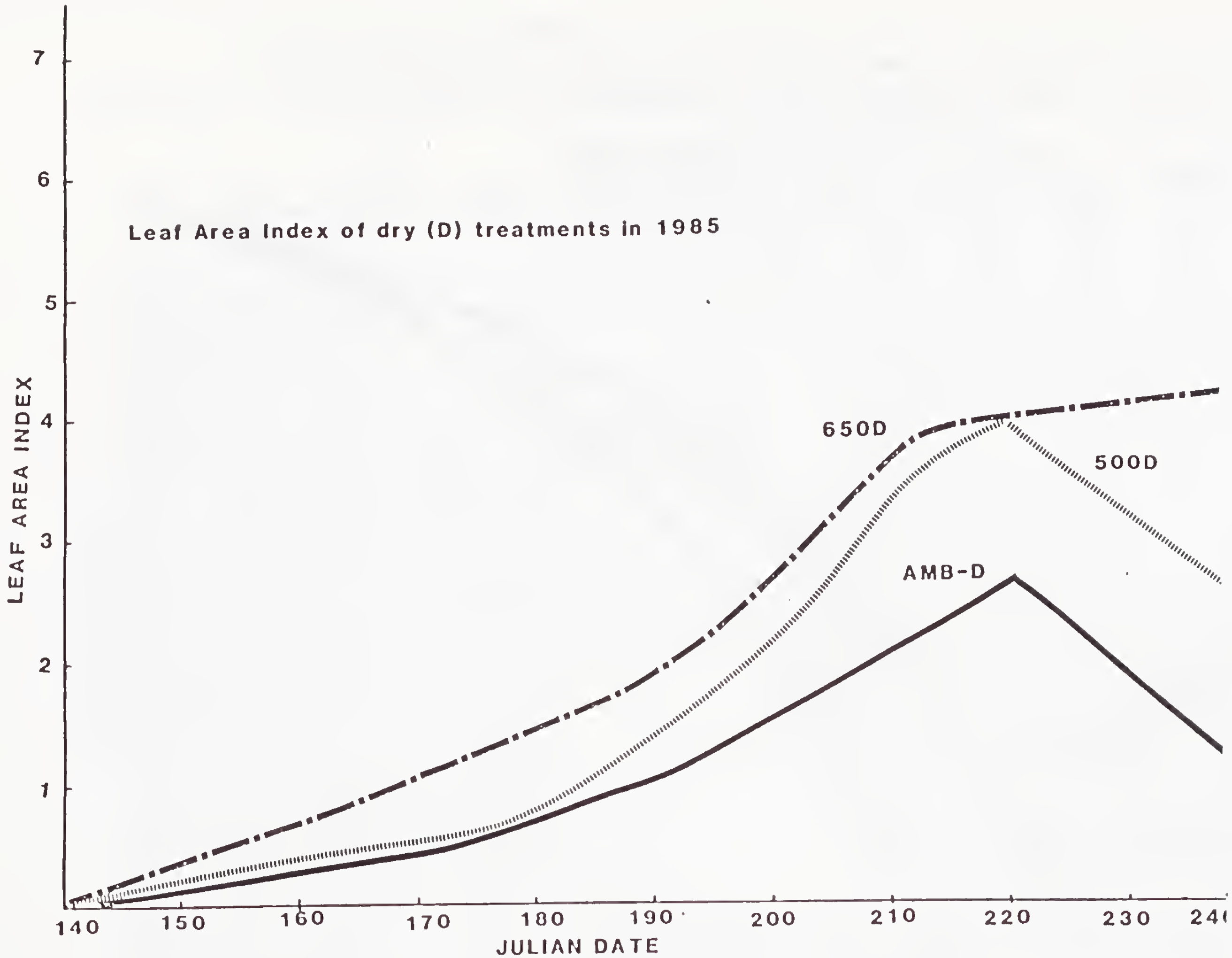

Figure 9. Leaf area index of the plants in the dry ambient, 500, and 650 $\mu\ell\ \ell^{-1}$ CO_2 chambers during the CO_2-cotton 85 experiment.

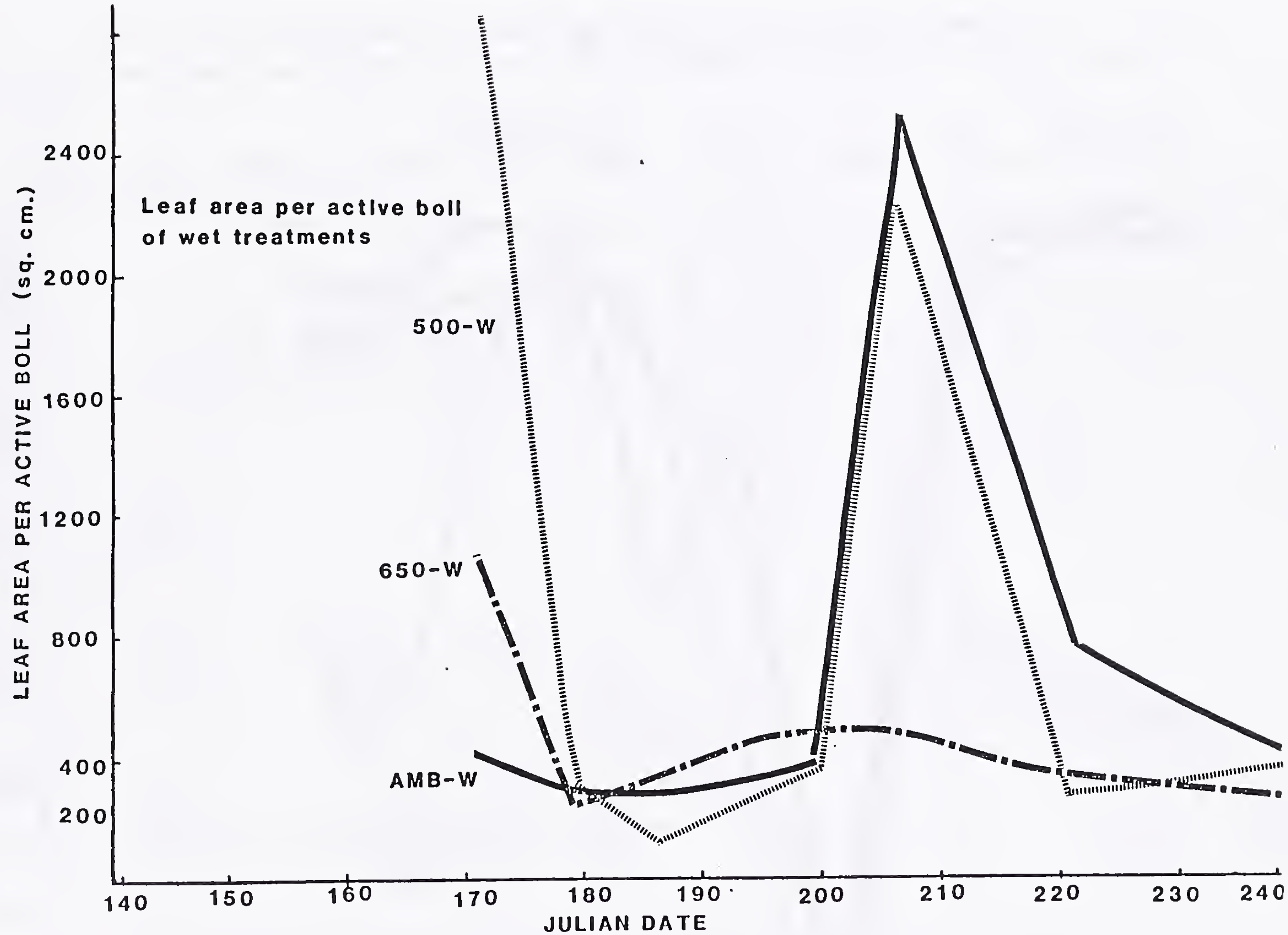

Figure 10. Leaf area per active boll on the plants in the wet ambient, 500, and 650 $\mu\ell\ \ell^{-1}$ chambers for the CO_2-cotton 85 experiment.

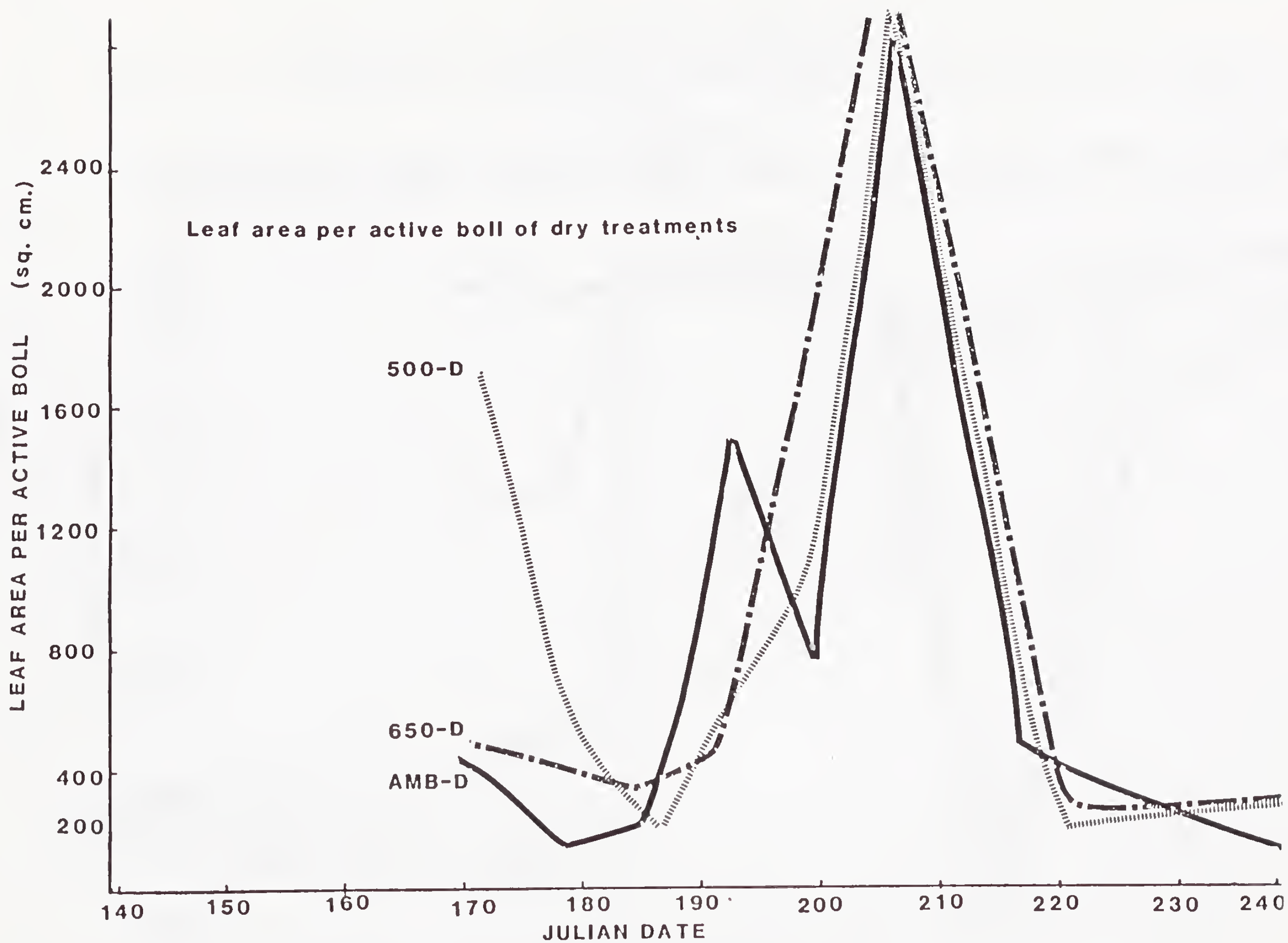

Figure 11. Leaf area per active boll on the the plants in the dry ambient, 500, and 650 µℓ ℓ^{-1} CO_2 chambers during the CO_2-cotton 85 experiment.

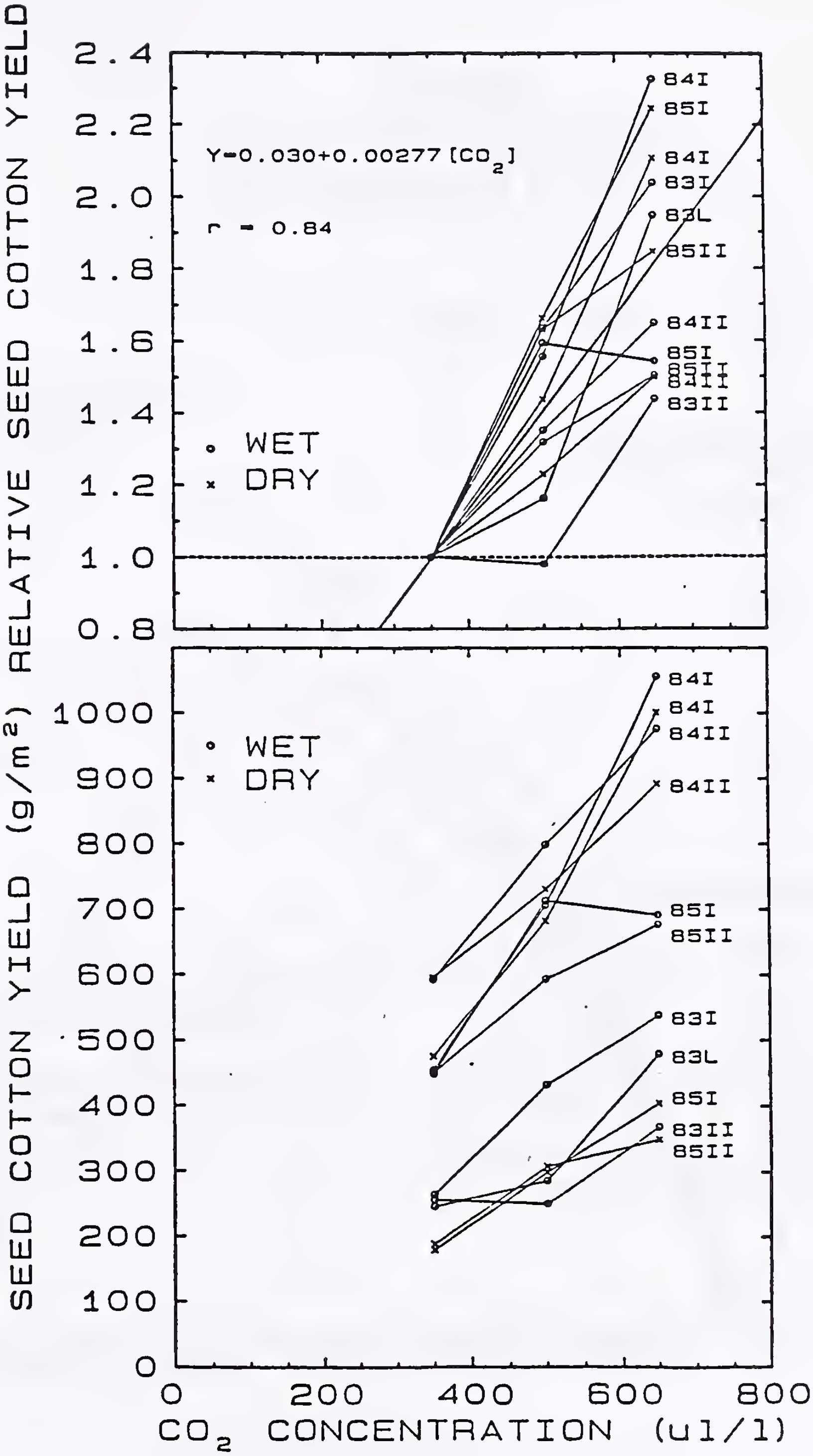

Figure 12. Seed cotton (lint plus seed) yield versus CO_2 concentration for the 1983, 1984, and 1985 experiments (lower graph). The seed cotton yield relative to that of the ambient control chambers is plotted in the upper graph. The labels on the right identify the year and replicate of the particular data points.

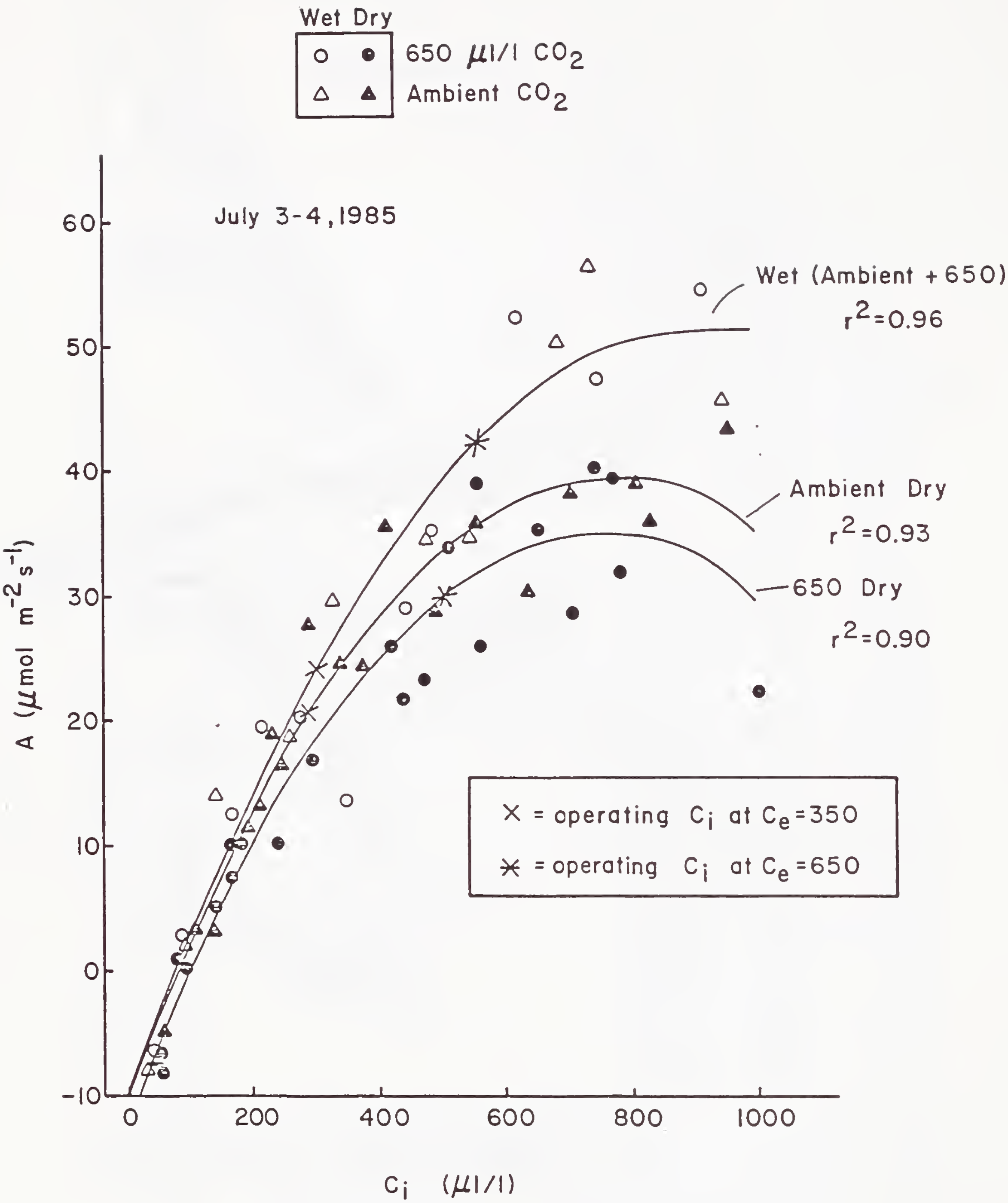

Figure 13. Assimilation rate (A) versus CO_2 concentration inside the substomatal cavities (c_i) on 3-4 July 1985.

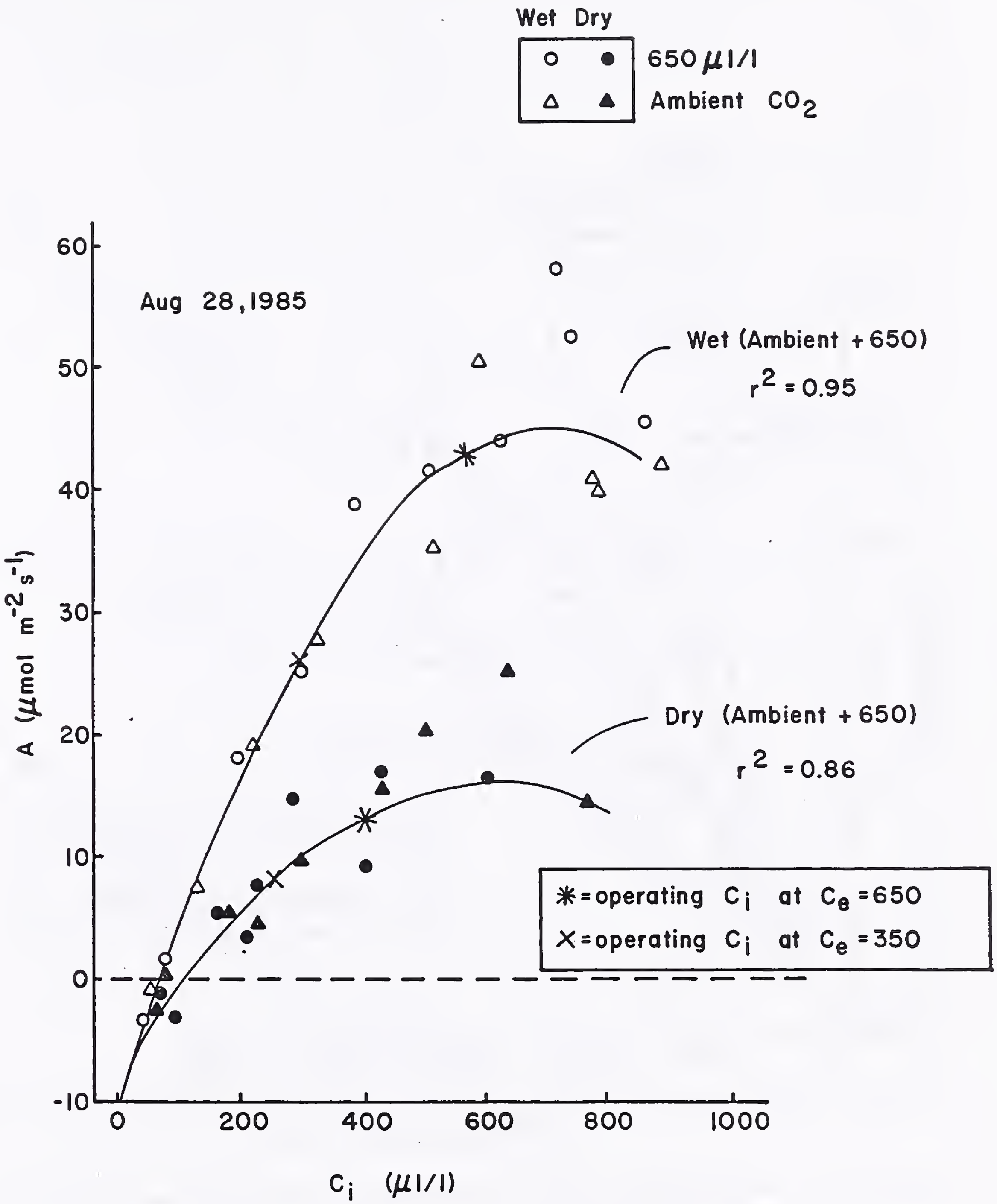

Figure 14. Assimilation rate (A) versus CO_2 concentration inside the substomatal cavities on 28 August 1985.

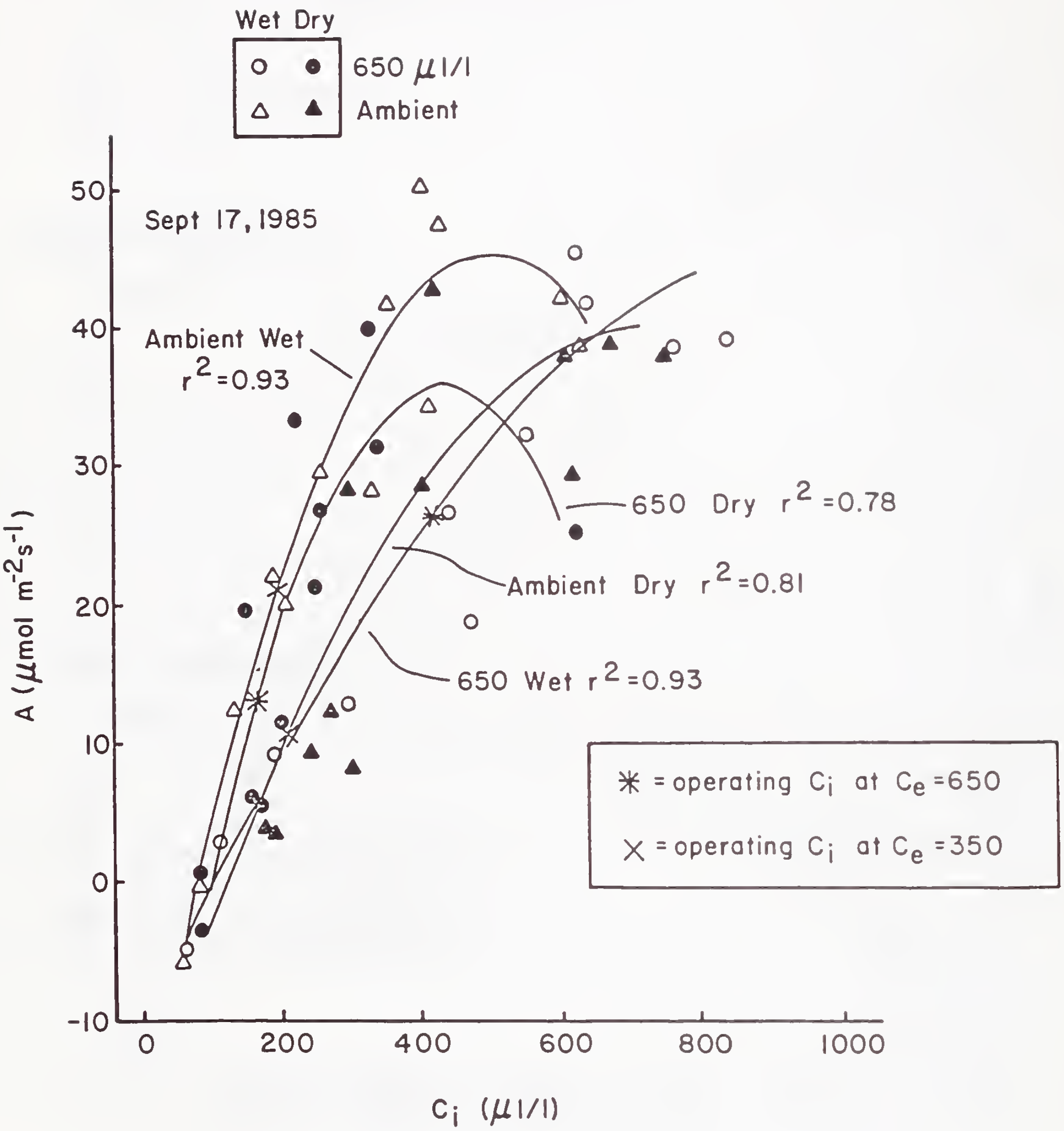

Figure 15. Assimilation rate (A) versus CO_2 concentration inside the substomatal cavaties on 17 September 1985.

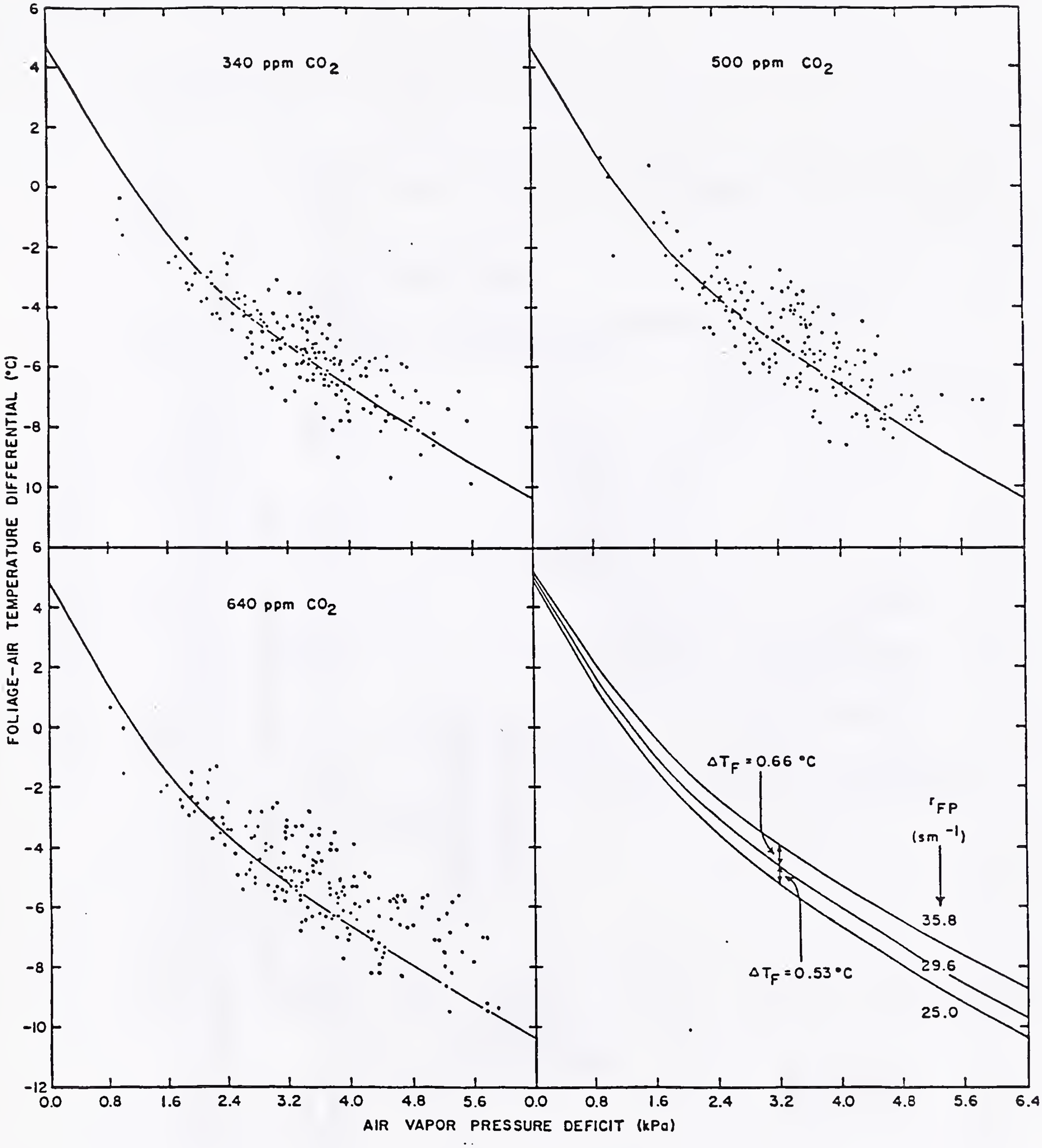

Figure 16. Foliage-air temperature differential ($T_F - T_A$) vs. air vapor pressure deficit (VPD) for cotton growing under three different atmospheric CO_2 concentrations and transpiring at the potential rates for those conditions. The solid dots are the data obtained during 1985. The solid lines passing through the three data sets are identical to each other and to the r_{FP} = 25.0 sm^{-1} non-water-stressed baseline of the lower right-hand section. The three baselines of this latter section are calculated from equation (1) for a representative R_N value of 525 Wm^{-2}, an r_A value of 15 sm^{-1} (as determined by Idso et al, 1986a), and the listed r_{FP} values determined in this study to prevail under the three different atmospheric CO_2 concentrations maintained in the chambers. The specified foliage temperature differentials (ΔT_F) between the 340 and 500 ppm baselines and the 500 and 640 ppm baselines are mean results for the entire air VPD range 0.0 to 6.4 kPa.

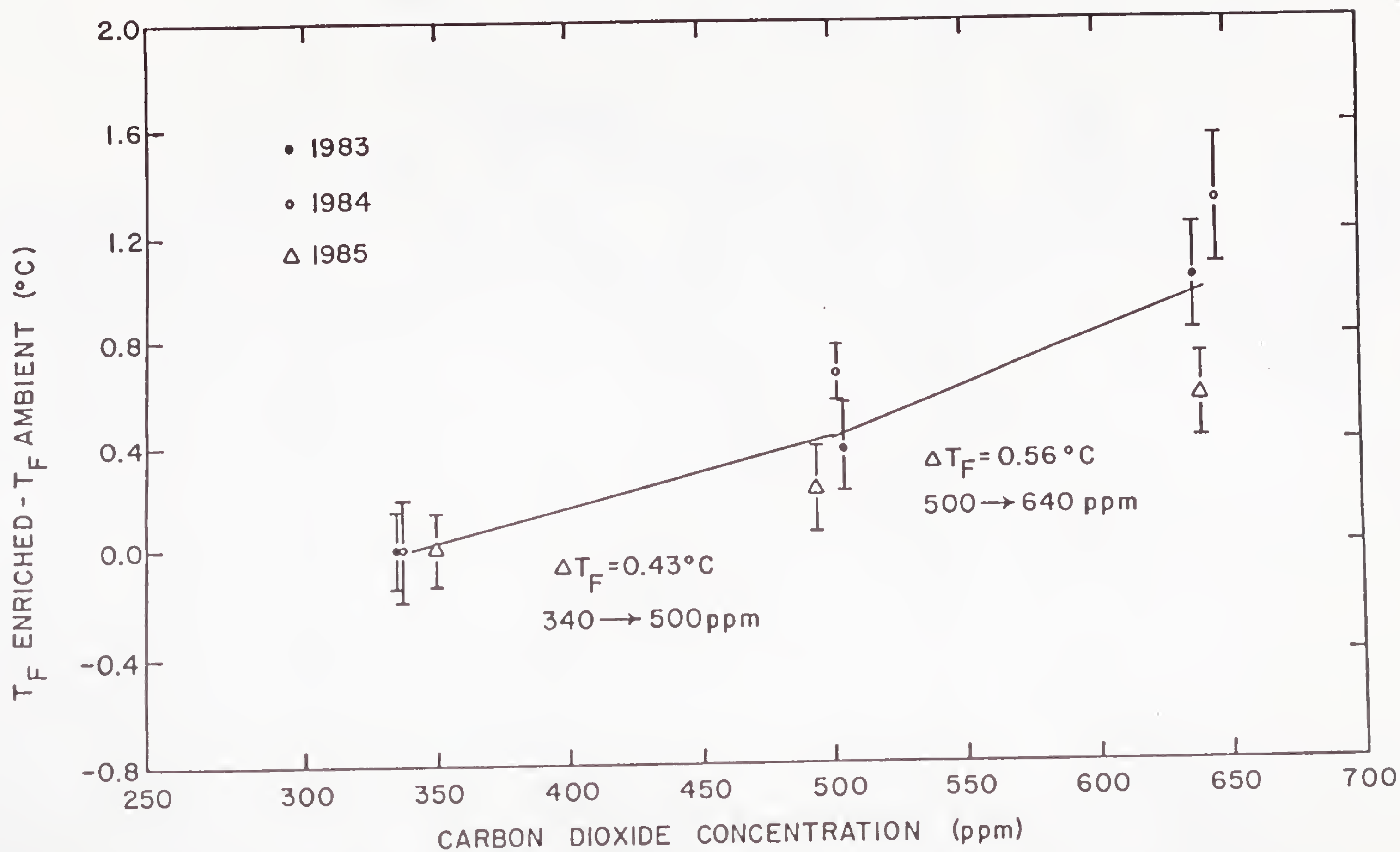

Figure 17. Cotton foliage temperature increases caused by atmospheric CO_2 enrichment in the three years of the study. Error bars represent 95 percent confidence intervals about the means. Solid trend lines represent results of linear regressions determined from the means.

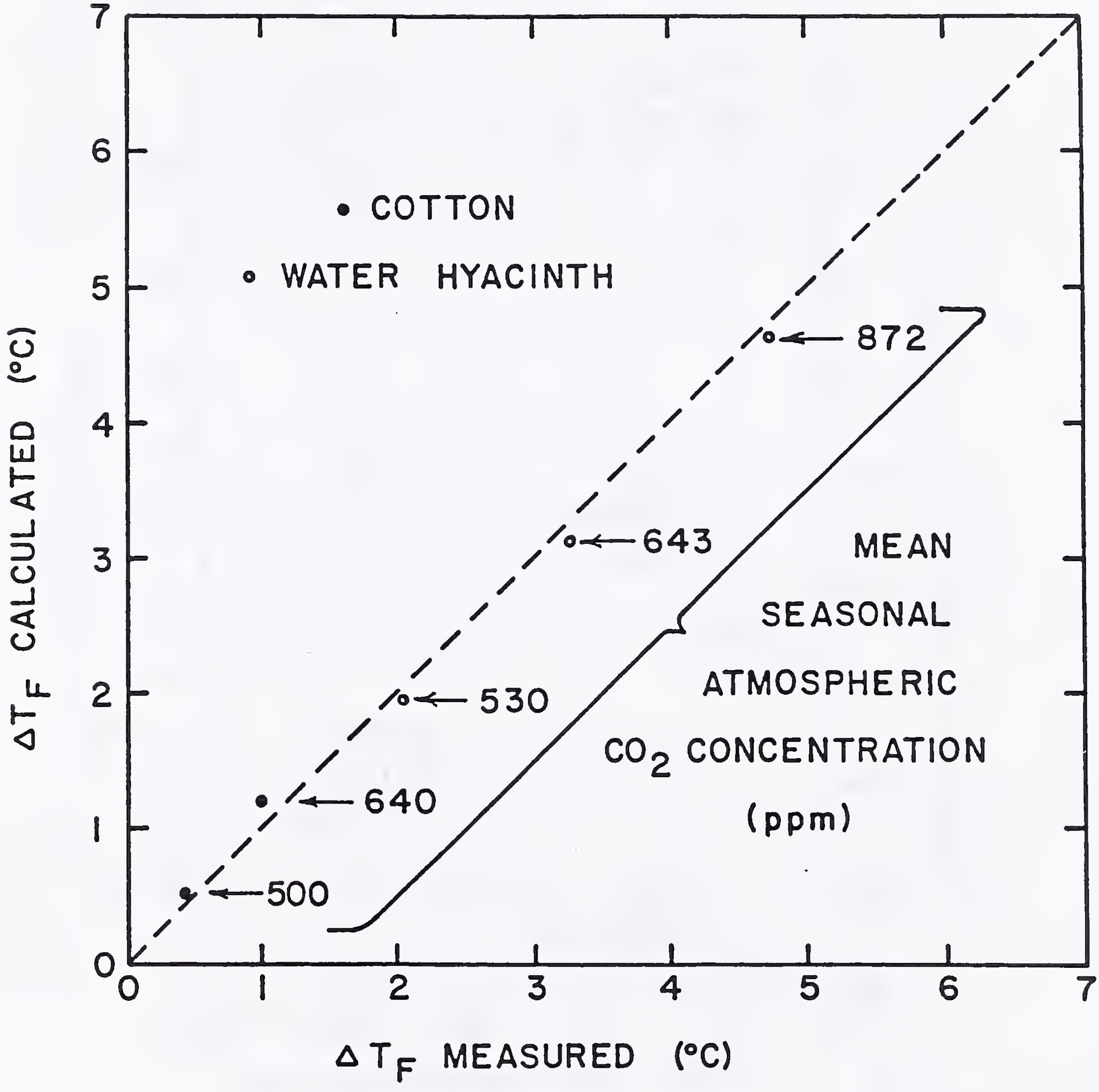

Figure 18. Calculated vs. measured foliage temperature increases caused by atmospheric CO_2 enrichment. The solid dots are the mean results for the 3-year cotton study, while the open circles are the results of a similar 1-year study of water hyacinths performed by Idso et al. (1986b). The dashed 1:1 line represents the locus of perfect agreement between calculations and measurements. The mean ambient atmospheric CO_2 concentration for both studies was 340 ppm.

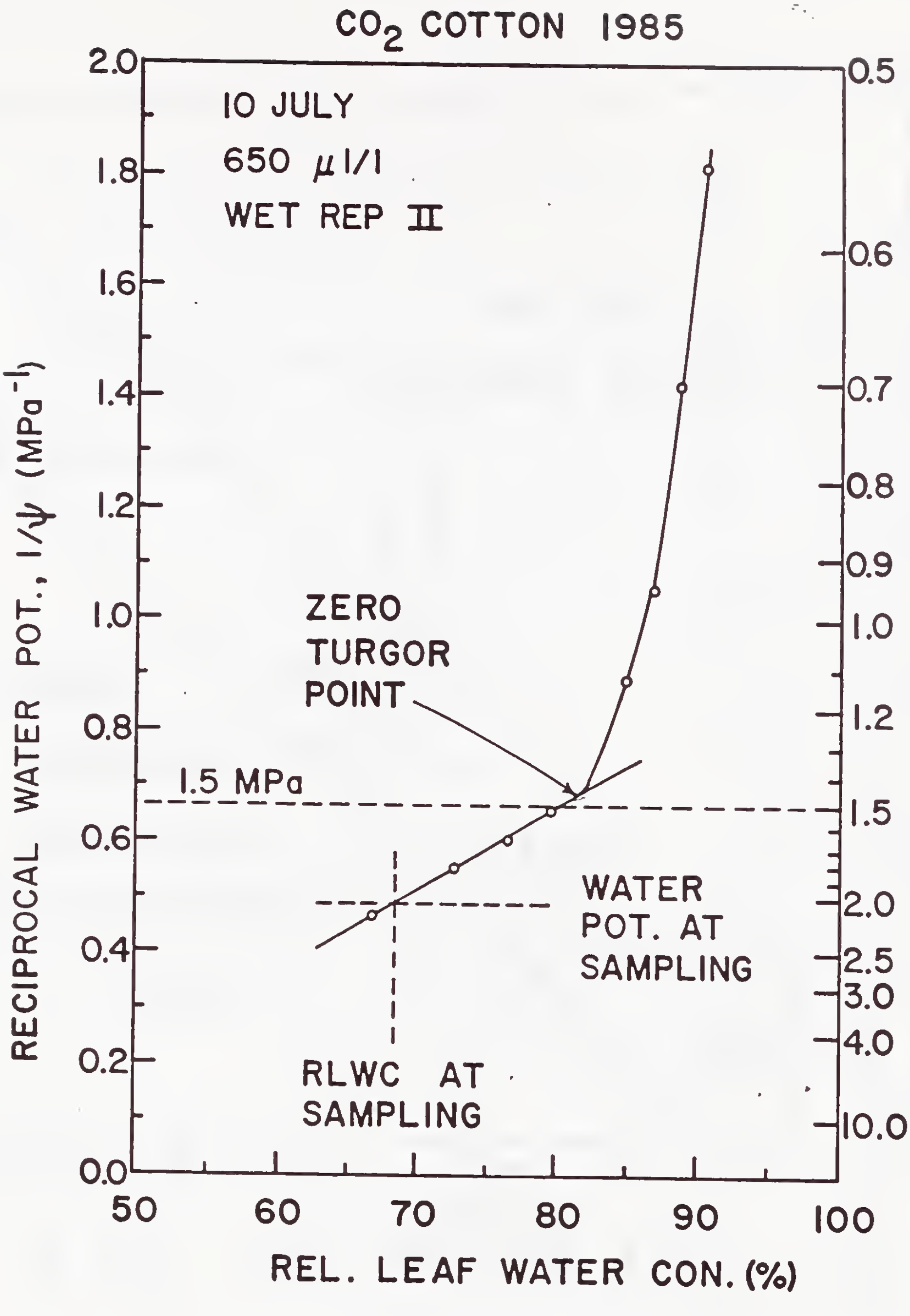

Figure 19. A "pressure-volume" curve for a leaf sampled on 10 July 1985 from the 650 μℓ ℓ$^{-1}$ CO_2 chamber. The reciprocal of the water potential determined from the pressure bomb is plotted against relative leaf water content determined from leaf weight.

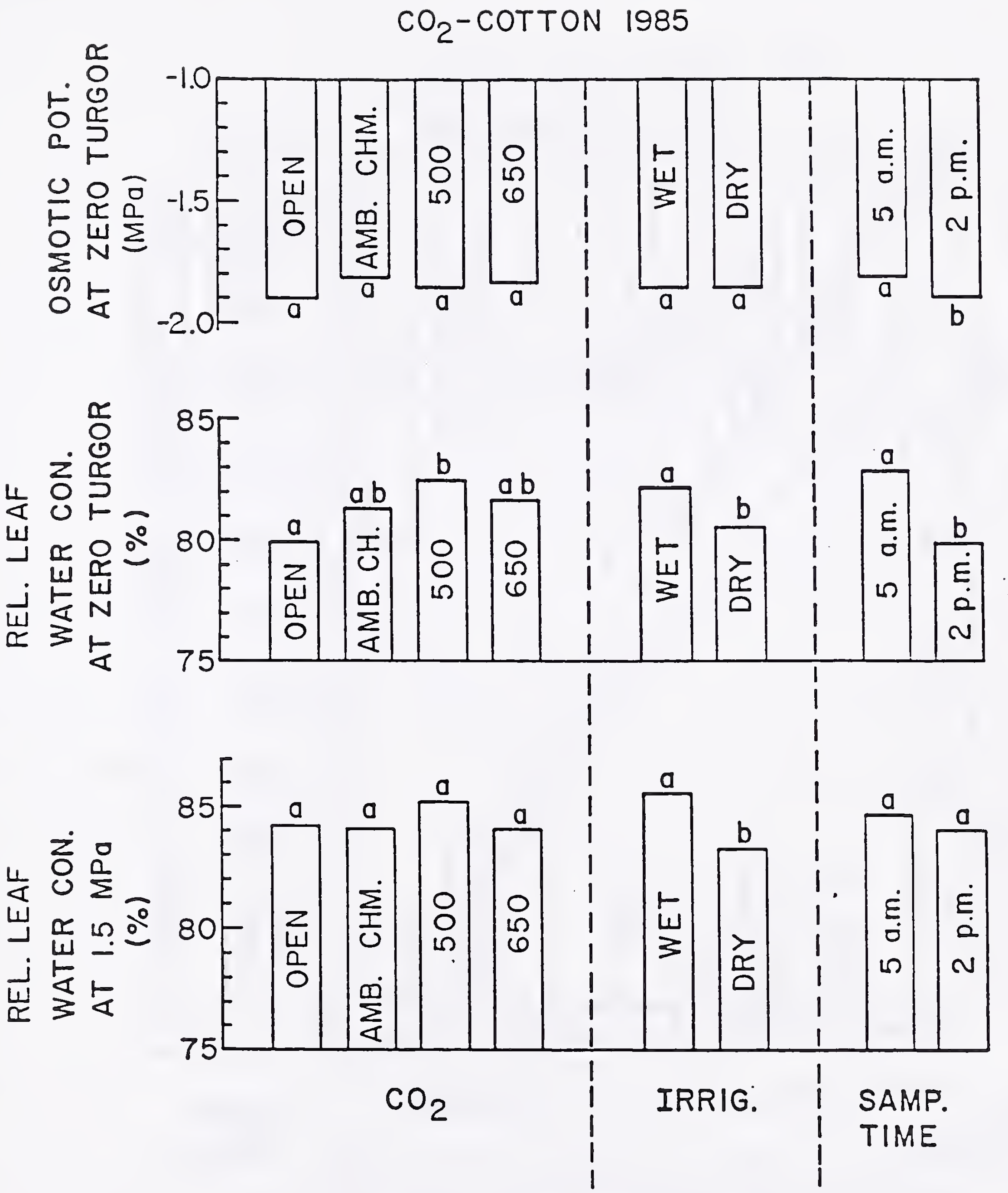

Figure 20. Mean values (a) of leaf osmotic potential at zero turgor, (b) of relative leaf water content at zero turgor, and (c) of relative leaf water content at 1.5 MPa, as affected by CO_2, irrigation, and sampling time in the CO_2-cotton 85 experiment. Means within each group that have the same letter are not significantly different at the 5% probability level.

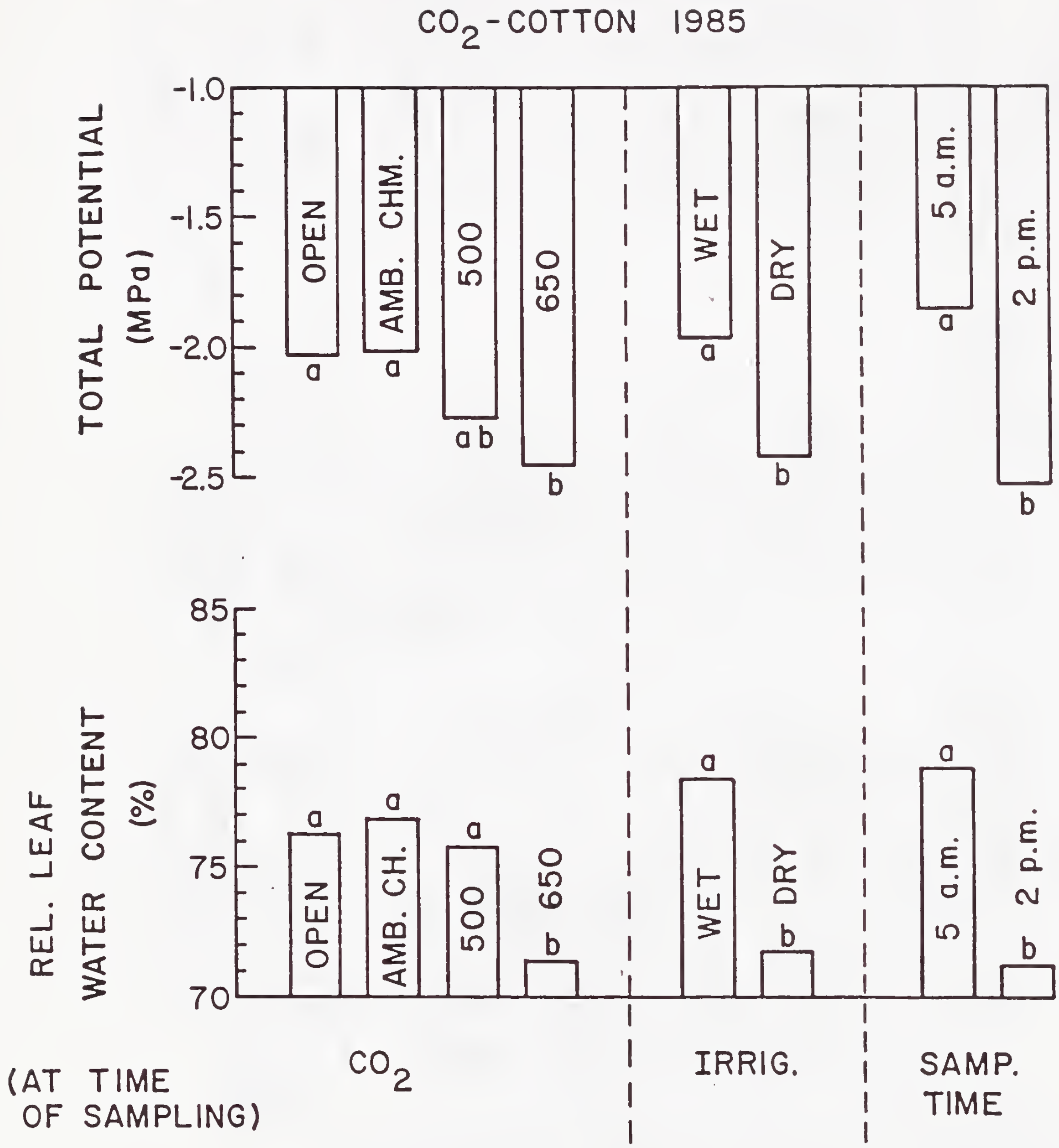

Figure 21. Mean values at time of sampling (a) of total leaf water potential and (b) relative leaf water content as affected by CO_2, irrigation, and sampling time in the CO_2-cotton 85 experiment. Means within each group that have the same letter are not significantly different at the 5% probability level.

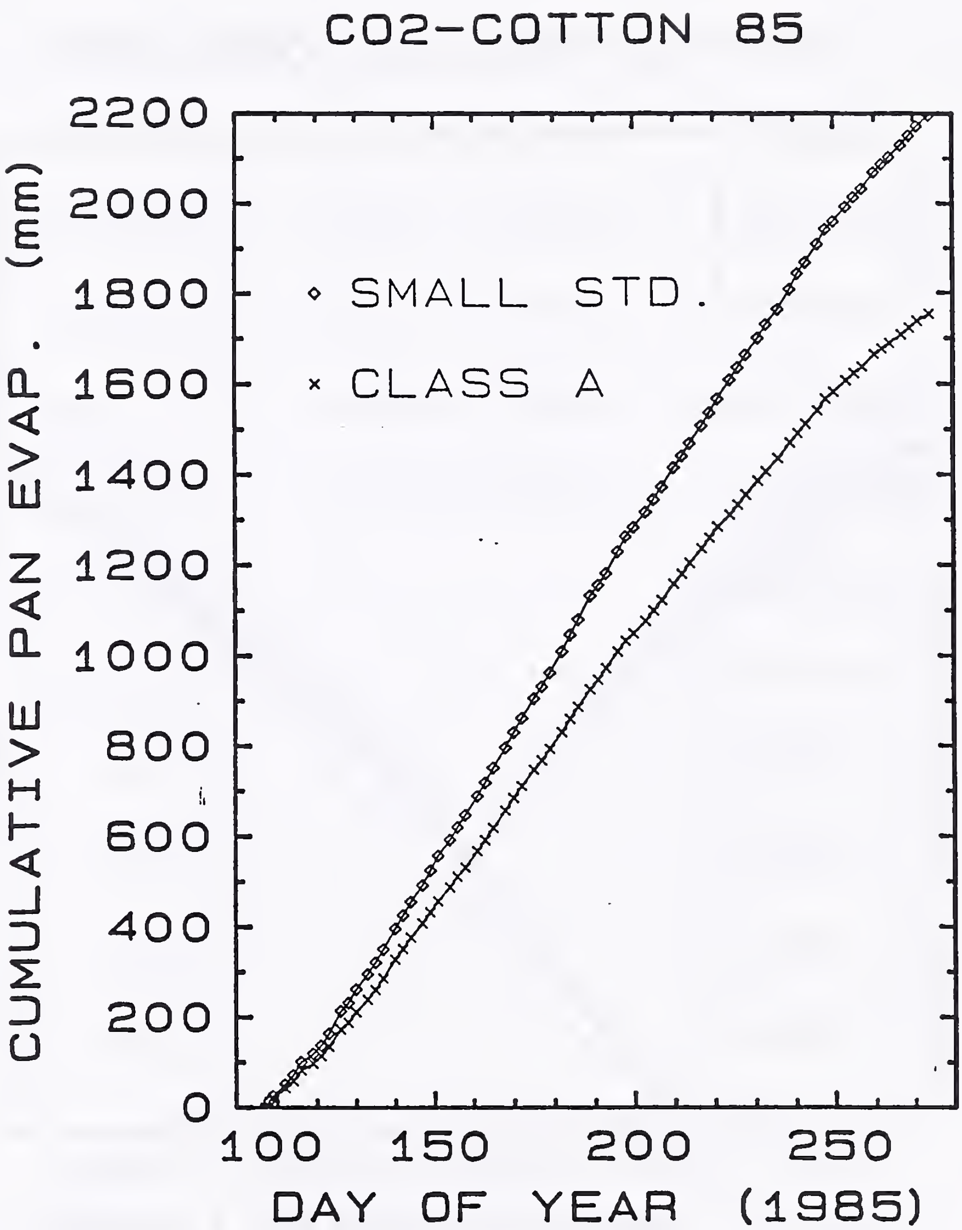

Figure 22. Cumulative pan evaporation through the 1985 growing season from a standard Class A pan over bare soil beside the cotton field and also from a small (250 mm-dia.) "standard" pan adjacent to the Class A pan.

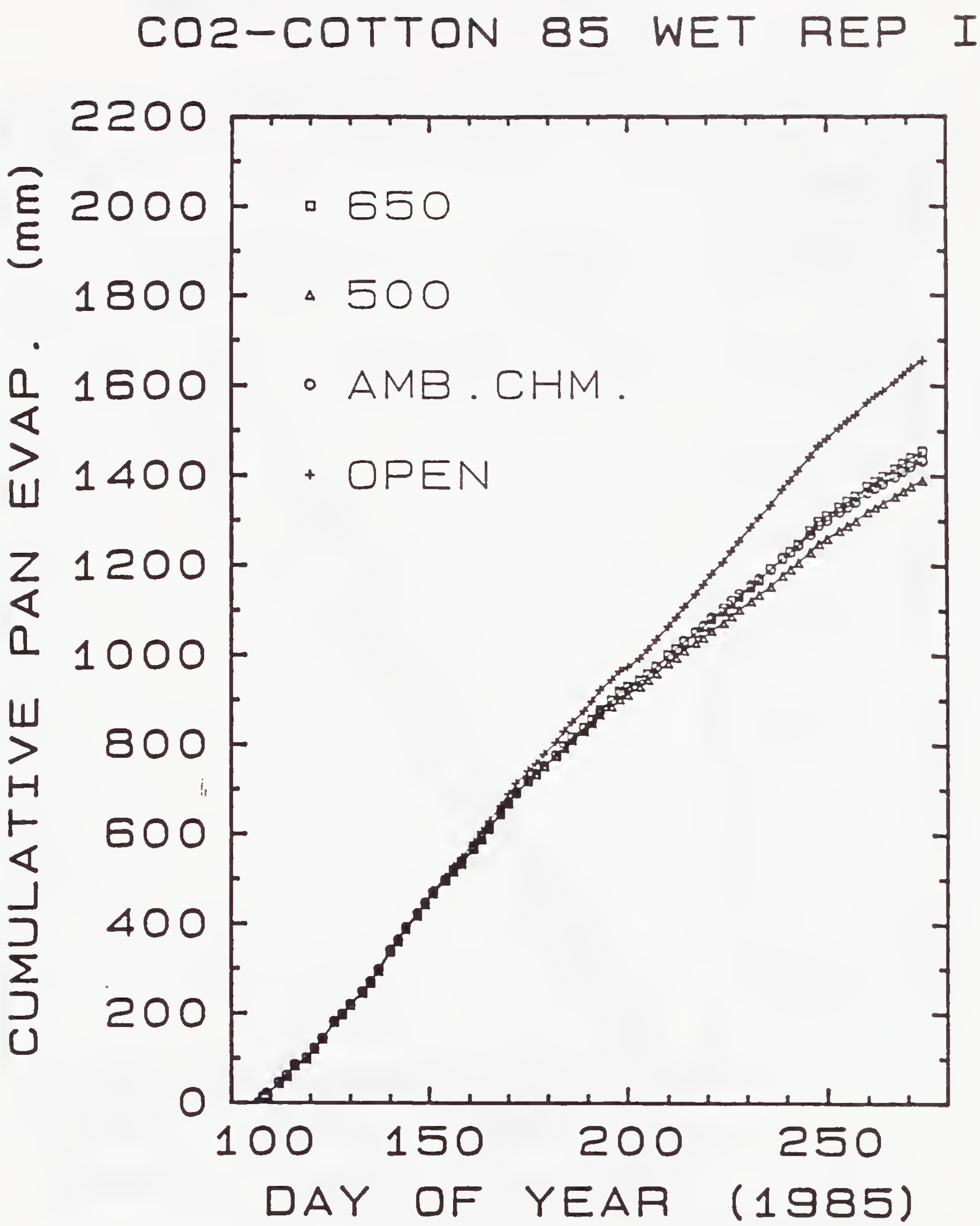

Figure 23. Cumulative pan evaporation through the 1985 growing season from small pans placed in the open field plot and the ambient, 500, and 650 μℓ ℓ$^{-1}$ CO_2 chambers of replicate I of the wet irrigation treatment.

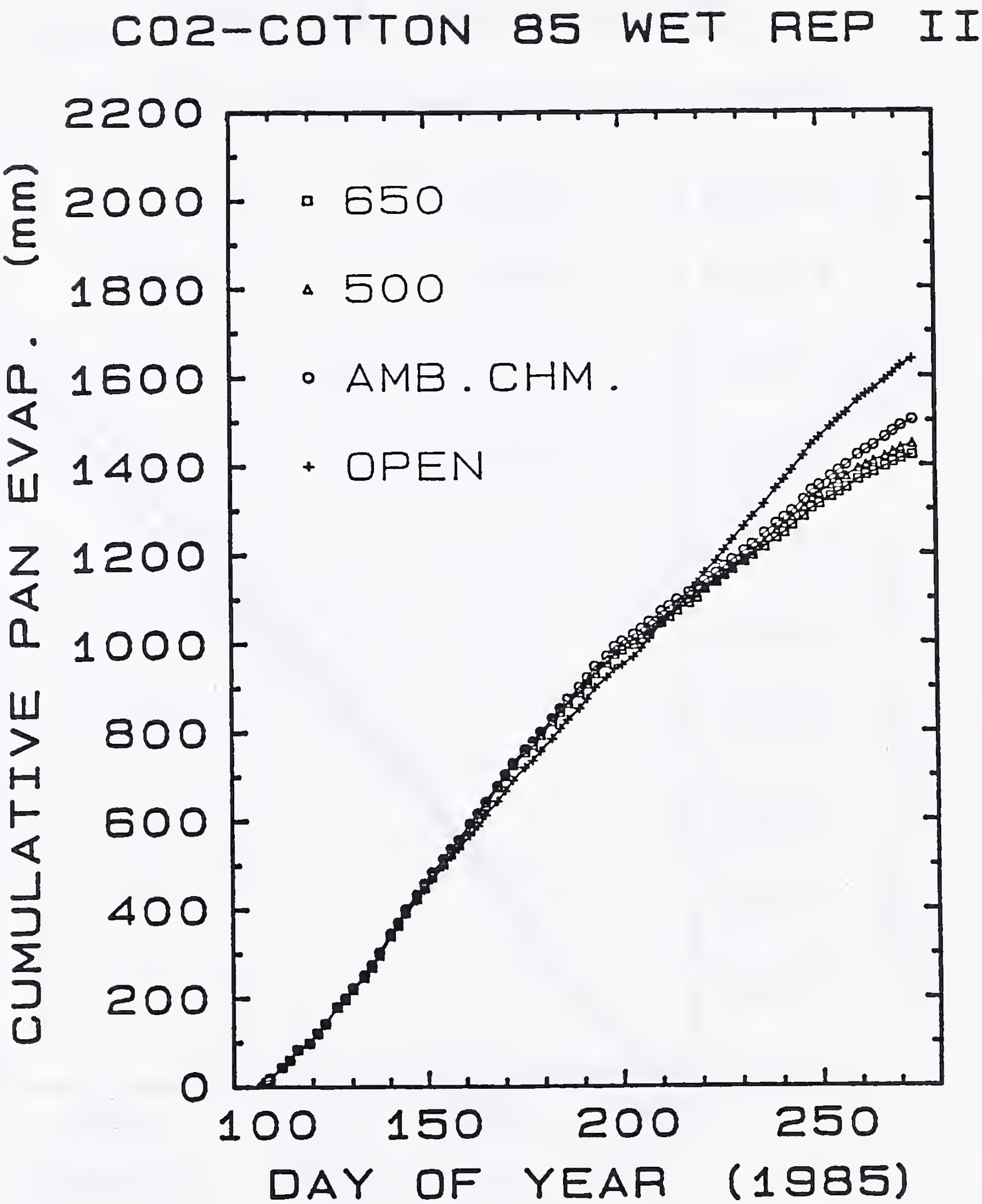

Figure 24. Cumulative pan evaporation through the 1985 growing season from small pans placed in the open field plot and the ambient, 500, and 650 µℓ ℓ$^{-1}$ CO_2 chambers of replicate II of the wet irrigation treatment.

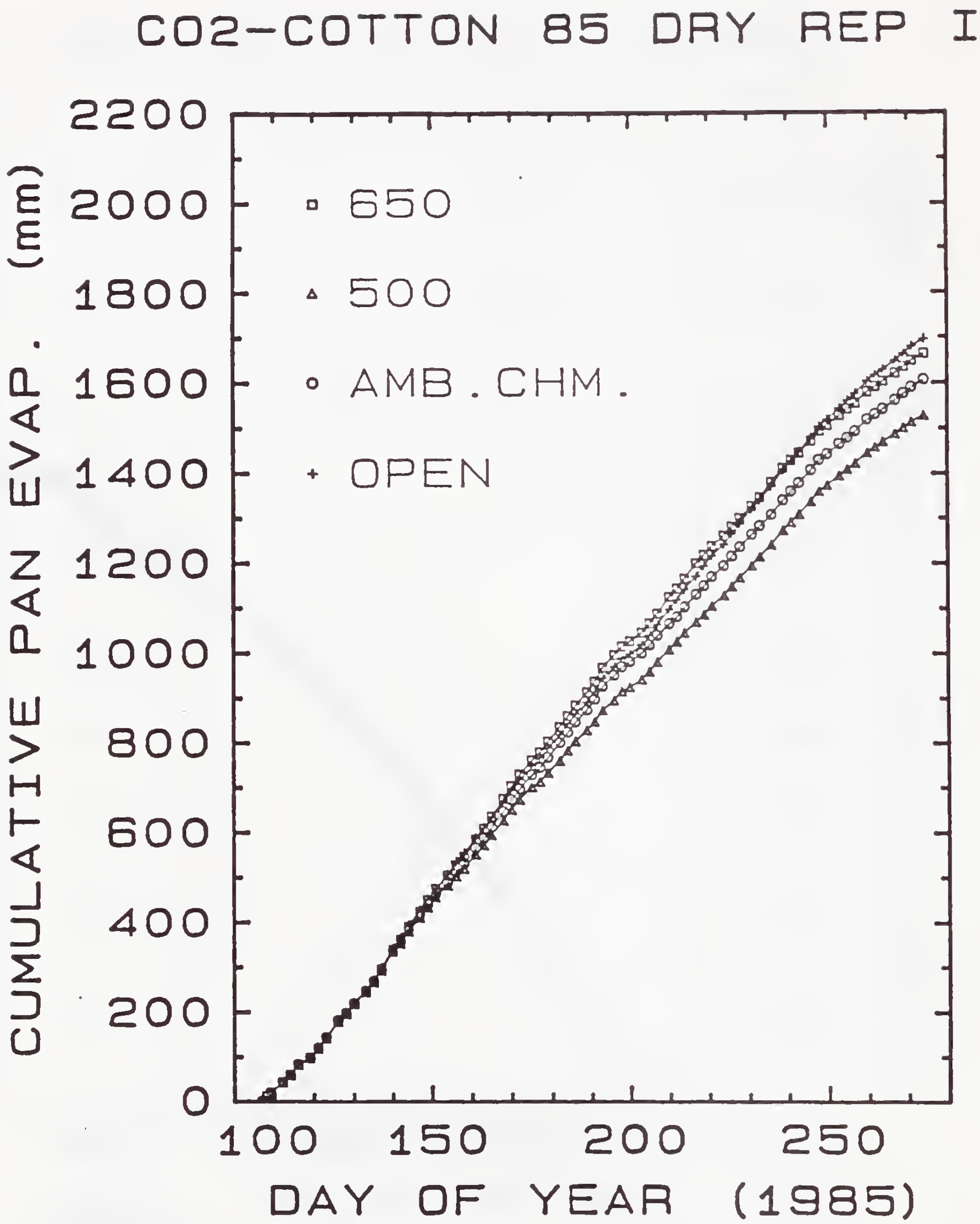

Figure 25. Cumulative pan evaporation through the 1985 growing season from small pans placed in the open field plot and the ambient, 500, and 650 µℓ ℓ^{-1} CO_2 chambers of replicate I of the dry irrigation treatment.

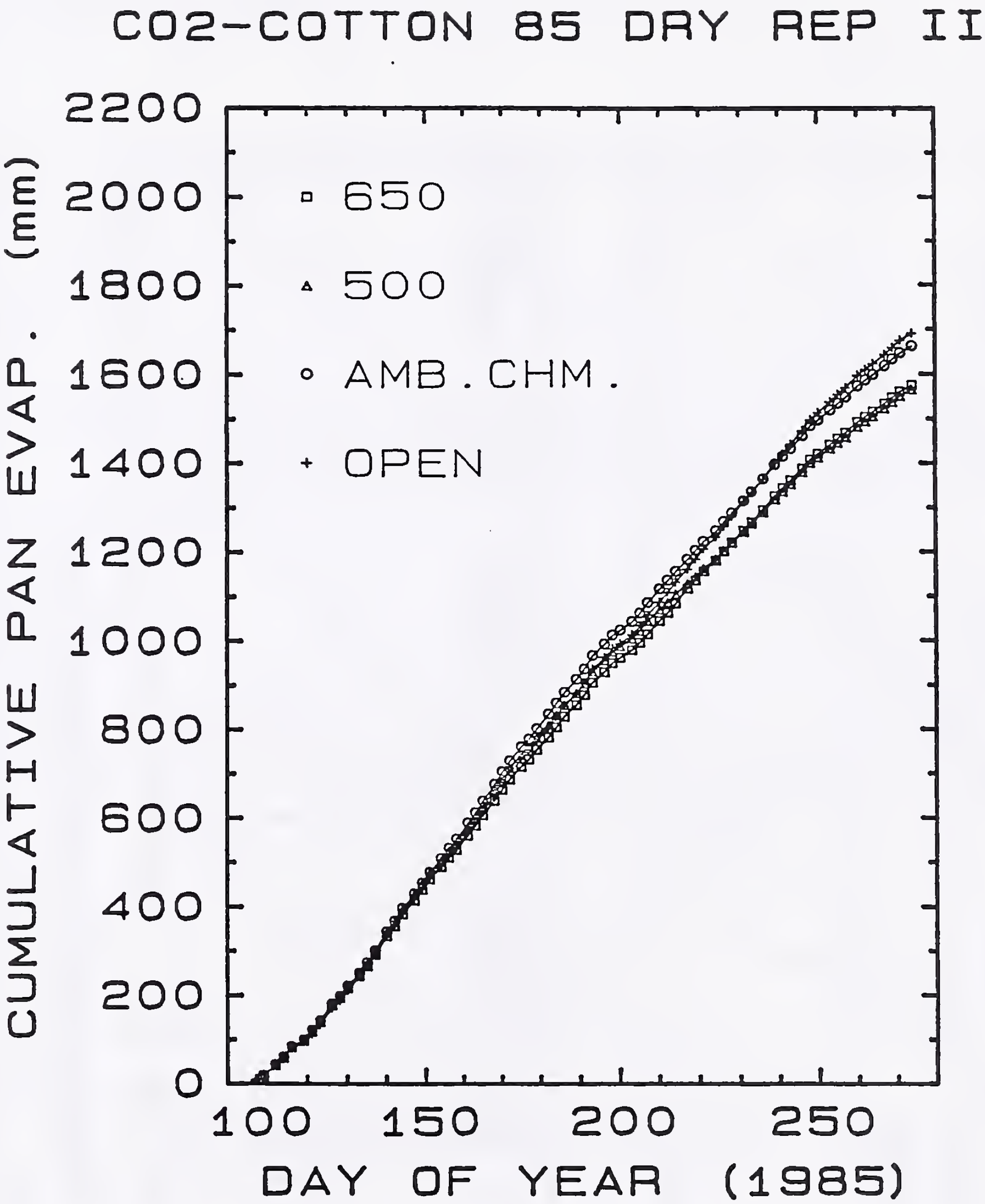

Figure 26. Cumulative pan evaporation through the 1985 growing season from small pans placed in the open field plot and the ambient, 500, and 650 $\mu\ell\ \ell^{-1}$ CO_2 chambers of replicate II of the dry irrigation treatment.

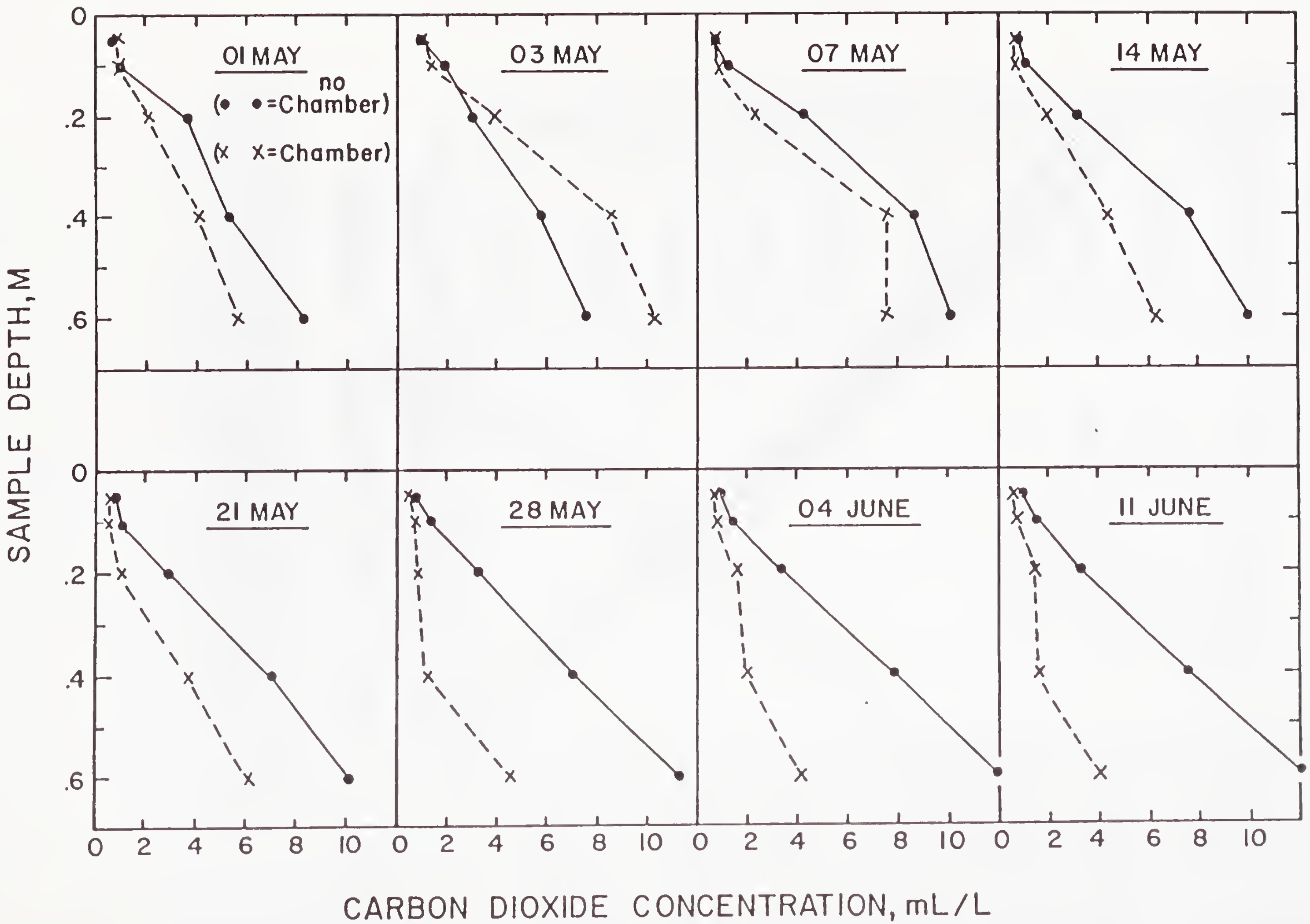

Figure 27. Soil carbon dioxide concentration distribution as a function of depth and time outside (no chamber) and inside the open-top chamber (May to June).

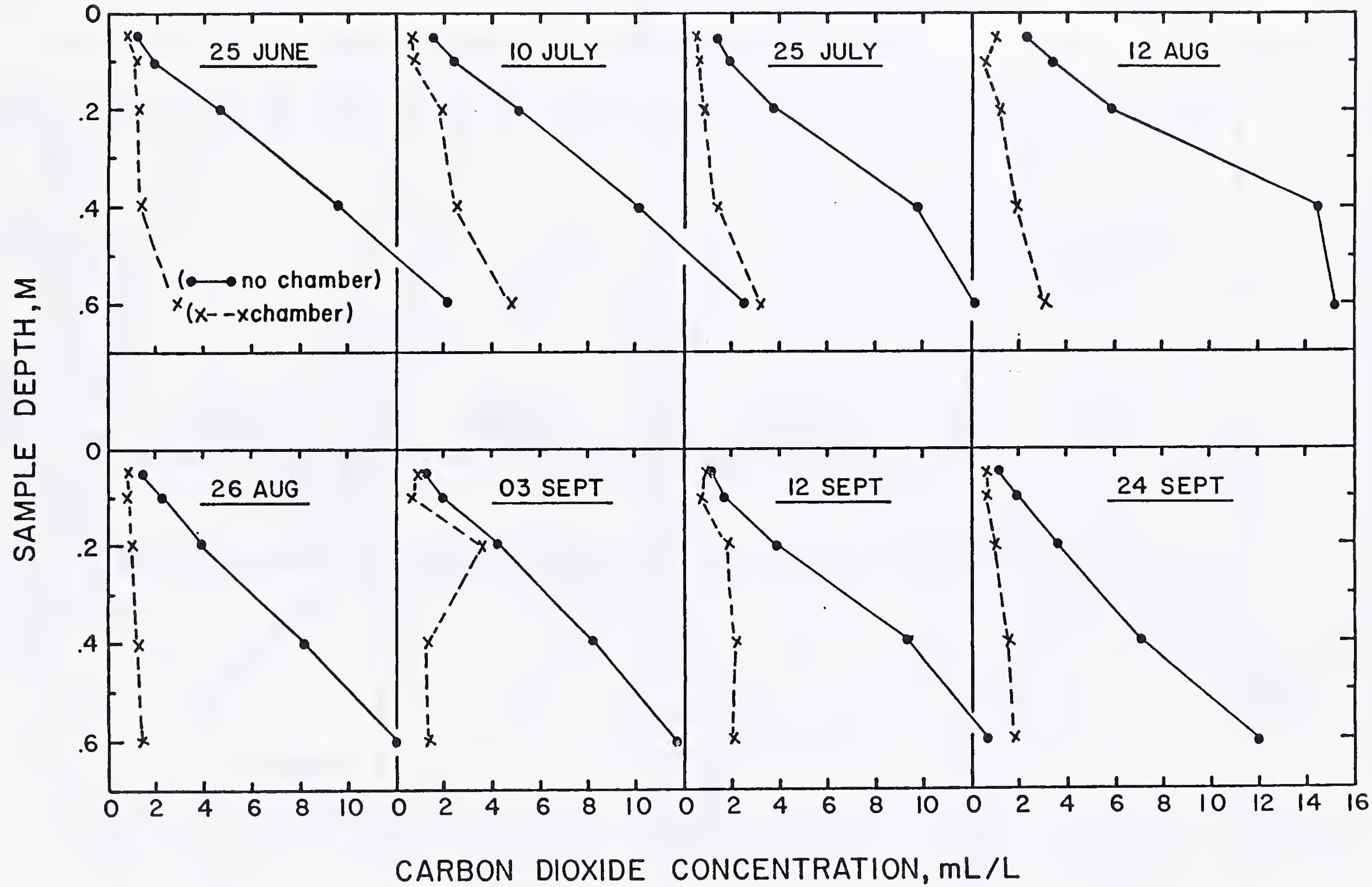

Figure 28. Soil carbon dioxide concentration distribution as a function of depth and time outside (no chamber) and inside the open-top chamber (June to September).

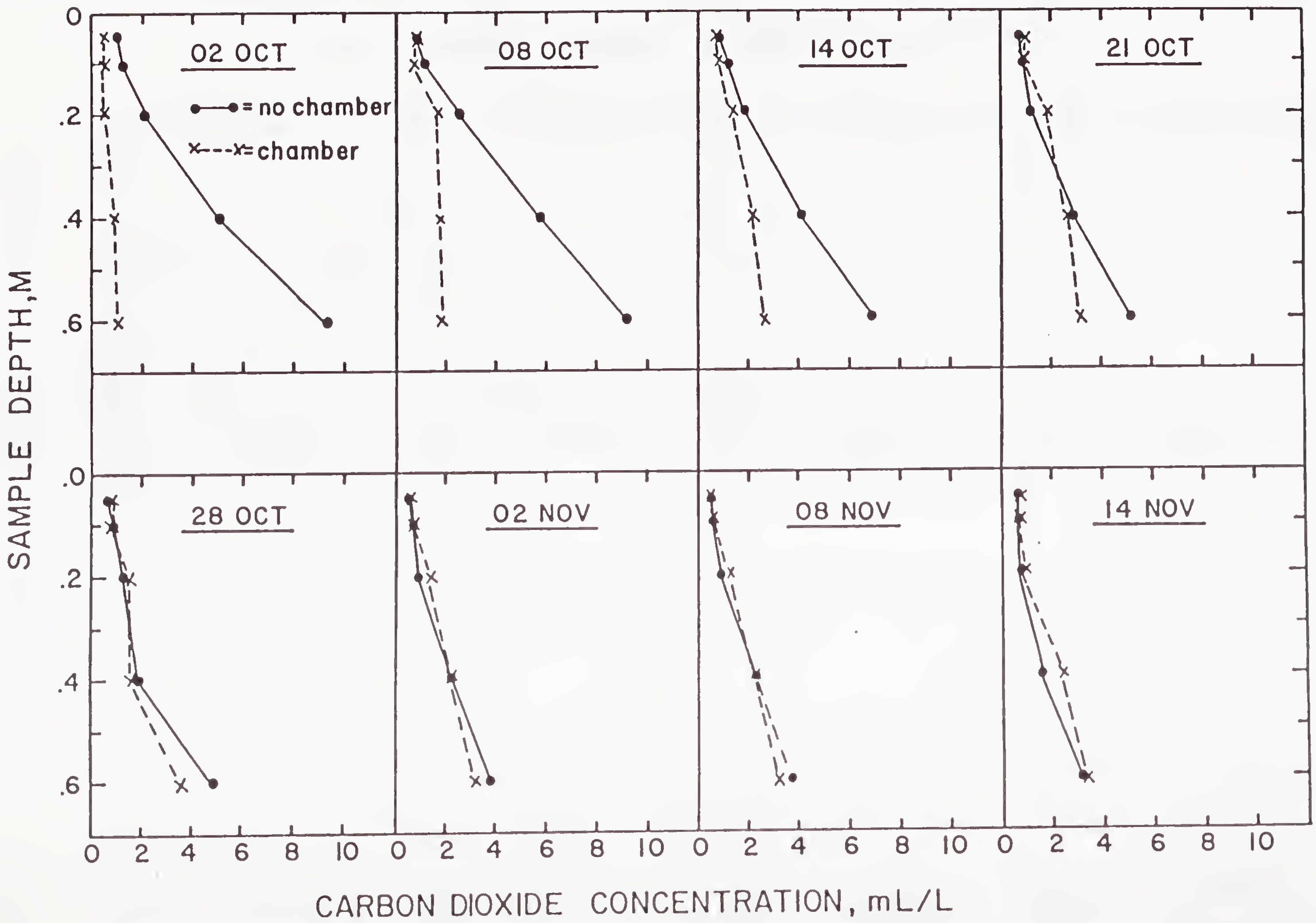

Figure 29. Soil carbon dioxide concentration distribution as a function of depth and time outside (no chamber) and inside the open-top chamber (October to November).

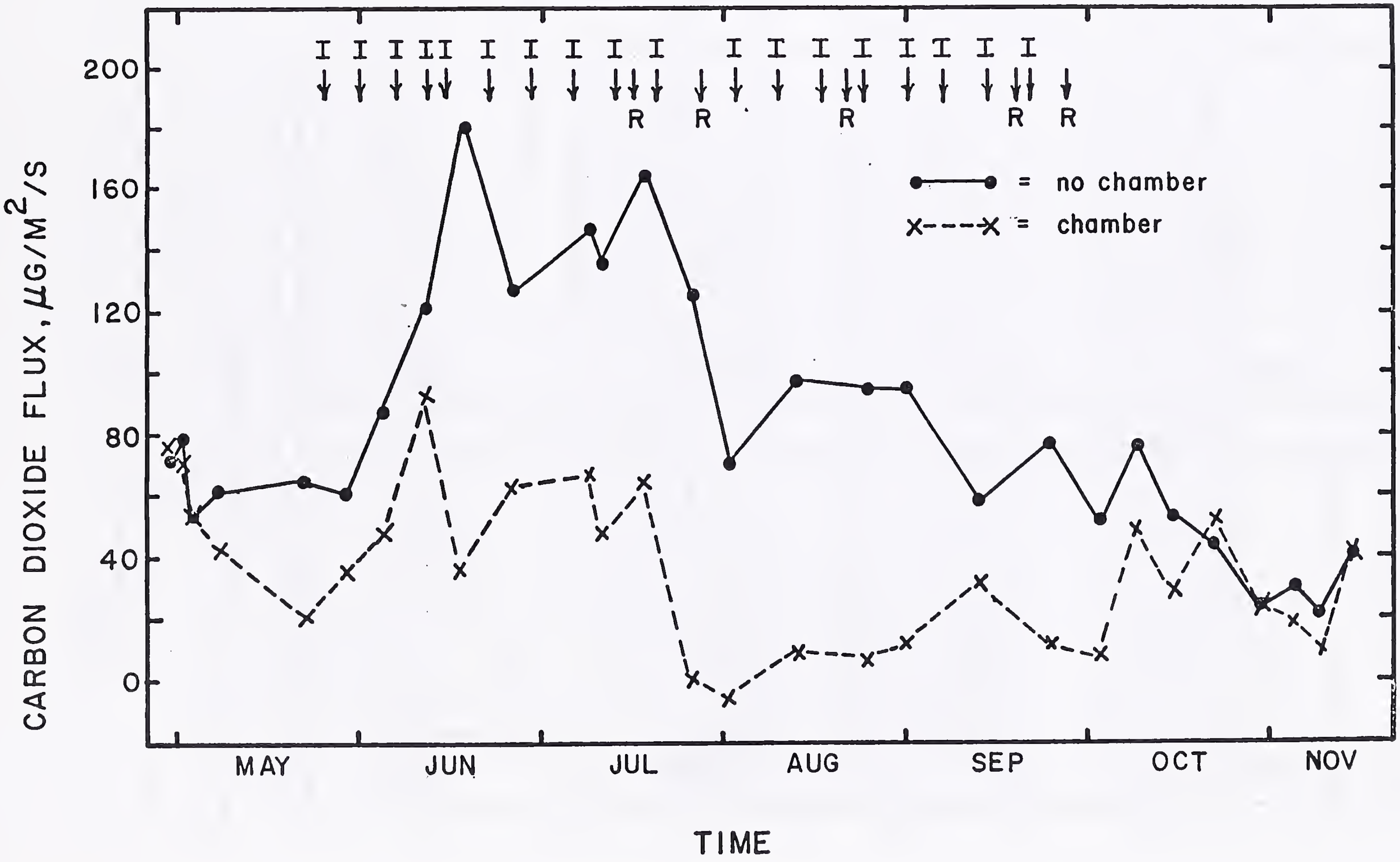

Figure 30. Soil carbon dioxide flux as a function of time outside (no chamber) and inside the open-top chamber.

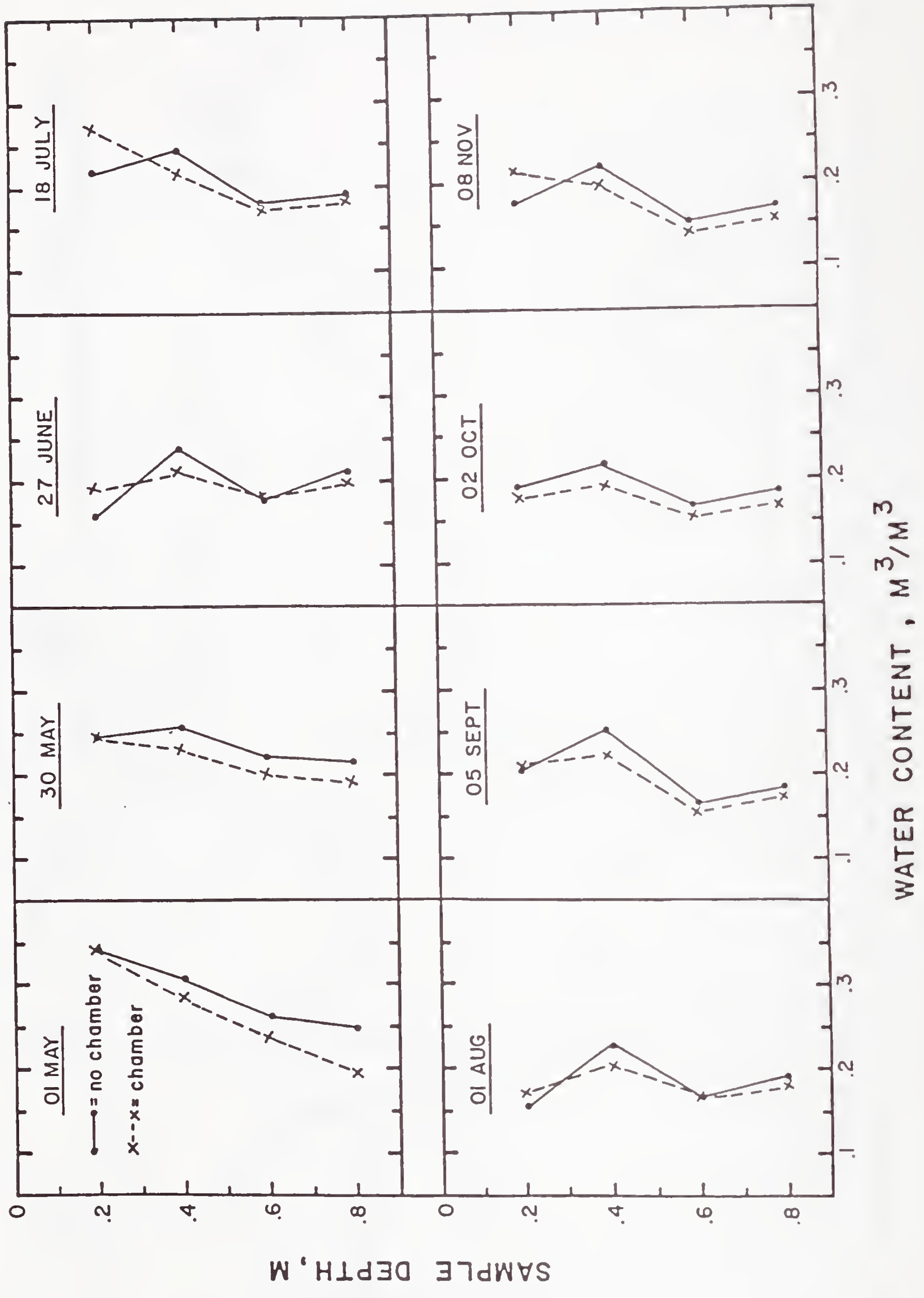

Figure 31. Soil water content distribution as a function of depth and time outside (no chamber) and inside the open-top chamber.

TITLE: DISTRIBUTION OF A MOBILE HERBICIDE BELOW A FLOOD-IRRIGATED FIELD

NRP: 20790 CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

Predicting the future quantity and quality of groundwater resources requires a better understanding of how water and chemicals move downward below the root zone. Deep percolation below flood-irrigated agricultural fields is the major contributor to groundwater recharge in many of the valleys of the arid western United States. Better field methods are necessary for evaluating the effects of flood-irrigation management on the nature and amount of deep percolation water.

In two earlier field experiments (see 1984 Annual Report), we found that downward velocities of percolating water, as measured by chemical tracers exceeded velocities predicted by simple water balance models by up to a factor of six. The accelerated leaching of surface-applied solutes was attributed to the presence of preferential flow paths in the soil. The purpose of the present study was to look at this preferential flow phenomenon in more detail, and to determine its effect on the distribution of a mobile herbicide under flood-irrigated conditions.

Bromacil (5-bromo-3-sec-butyl-6-methyluracil) is a photosynthesis inhibitor used primarily on non-cropland areas for control of annual and perennial grasses and broadleaf weeds. It also finds use for weed control in citrus orchards and pineapple plantations. It was chosen for this study primarily for its physical and chemical characteristics; bromacil is relatively non-volatile, is resistant to microbial degradation in soils, and is not strongly sorbed by most soils. Thus, it appeared to be well-suited for a several-month-long study of pesticide movement under field conditions.

MATERIALS AND METHODS

Bromacil

Some properties of bromacil pertinent to the experiment are presented in Table 1. The soil-related "properties" of organic carbon partition coefficient and degradation half-life listed in Table 1 serve only as general guidelines. Analytical standard bromacil (> 99% purity) for methods development was obtained from E. I. duPont deNemours and Company, Agricultural Chemicals Department, Wilmington, Delaware 19898. For field experiments, the commercial formulation Hyvar-X (80% bromacil by weight) was used. Hyvar-X is a wettable powder. To increase the solubility of Hyvar-X for the purpose of spraying a concentrated bromacil solution on the field, Hyvar-X was dissolved in a KOH solution. The ratio of Hyvar-X to 86% KOH was 2.3:1 by weight.

Field Plot Design

The 0.62-ha field plot, located at the Maricopa Agricultural Center of the University of Arizona, and which was described in the 1984 Annual Report, was again used for this experiment. The field was harrowed and new berms thrown up prior to the present experiment. A ditcher was used to form the berms in order to prevent the formation of a "well" along the perimeter of each subplot. Again this year, 56 equal-area subplots were established, each with an area of 7.6m by 10.7m. The smaller subplot size compared to the 9m by 12m of the 1984 experiment was due to the larger berm width resulting from use of the ditcher.

Experimental Procedure

Following a 125mm irrigation without chemical addition, five 75mm irrigations, each labeled with a different tracer and/or bromacil, were applied to the field plot over an eleven week period. Prior to each 75mm irrigation, 14 of the 56 subplots were sprayed with tracer or tracer/herbicide solution. The schedule of irrigations and associated chemicals is presented in Table 2. A separate tracer or tracer/herbicide formulation was prepared for each of the 14 treated subplots. Each tracer was converted to its potassium salt and dissolved in 32L of water. This solution was sprayed on the soil by making five to six passes with a hand-held spray rig over each 7.6m by 10.7m subplot. For the Br^- tracer only, an additional 14 subplots, for a total of 28, were sprayed with tracer solution.

Following the PFBA/Hyvar-X application (see Table 2), but prior to the addition of irrigation water, the surfaces of three of the treated subplots were sampled to determine the tracer/herbicide application uniformity. Thirty randomly selected points within each subplot were sampled to a depth of approximately 50mm using a 23mm I.D. Veihmeyer tube tip. These surface samples were analyzed for PFBA content via high-performance liquid chromatography (HPLC).

Soil cores from all 28 treated subplots were obtained during the four-day period June 11-14. The cores were taken using Veihmeyer tubes equipped with 21mm I.D. tips. Seven cores, in 300mm increments to a depth of 2.7m, were taken in each of the 14 subplots which had received all five tracers and Hyvar-X. An additional seven cores, in 300mm increments to a depth of 1.8m, were taken in each of the 14 subplots which received only Br^-. Thus, a total of 196 points were sampled. The locations of the sampling points are indicated in Figure 1. Each 300mm soil core was placed in a Ziploc bag and the bag put into an ice chest to minimize bromacil degradation after sampling. Upon return to the laboratory, all samples from the bromacil-treated plots were frozen until analysis; the samples from plots which received only bromide were stored at room temperature.

A subsample of each 300mm core was extracted with water at a 1:2 solution-to-soil ratio. After centrifugation and filtering, tracers and bromacil were analyzed via a HPLC technique described earlier (Bowman,

1984). Note that neither the extraction procedure nor HPLC analysis was optimized for bromacil; the bromacil concentrations determined to date must be considered qualitative. Analyses of bromacil in the soil samples making use of an organic solvent extraction and optimized chromatographic procedure are in progress.

RESULTS AND DISCUSSION

The results of the surface sampling for determining spray uniformity are presented in Table 3. There was a large degree of variation in recoveries from the 23mm I.D. samples. Coefficients of variation (CV) ranged from 31% to 51% within a single subplot. Two samples in subplot 4, and one sample in subplot 2, showed no presence of PFBA. The high CV's are perhaps not surprising given the small size of the samples relative to the subplot size. In addition, the subplot surfaces were not perfectly smooth; the uneven surface undoubtedly contributed to non-uniform spray application at the scale of the 23mm I.D. sample.

The recoveries of PFBA from subplots 2 and 13 (86% and 94%, respectively) are reasonable, although the recovery from subplot 4 (69%) seems rather low. Some loss was likely due to aerosol drift away from the subplots during application; this phenomenon was noted during spraying. It is also likely that some tracer was lost to the subplot berms in the attempt to spray every portion of the 7.6m by 10.7m subplot, thus lowering the actual surface concentration in the sampled areas. Another possibility, which cannot be discounted, is that some photodegradation of PFBA occurred during the afternoon and morning between PFBA spraying and sampling. Finally, it is possible, although not likely, that all the surface PFBA was not recovered by sampling to a 50mm depth.

As noted above, bromacil analyses are still in progress. Preliminary laboratory batch equilibration studies indicated a bromacil distribution coefficient on the Mohall soil from the field site to be on the order of 0.5mL g^{-1}. Therefore, total recovery of bromacil from the field cores is not achieved by simple extraction with water. Nonetheless, the aqueous extracts showed definite trends in bromacil distribution with depth for individual core samples. While the bromacil was not totally recovered in these extracts, it is felt that the water-extractable bromacil distribution with depth likely mirrored the distribution of total soil bromacil with depth. The following discussion is based on the water-soluble bromacil data.

Data for bromacil and PFBA distributions with depth for a representative core sample are presented in Figure 2. As expected, in most cores the bromacil peak concentration occurred at a shallower depth than did the peak for PFBA. The ratio of the PFBA peak depth to the bromacil peak depth is the retardation factor, R, which expresses the relative mobility of an unretained water tracer to a chemical which is retarded in its movement.

For the 77 core samples which have been analyzed up to this time, the bromacil retardation factors ranged from 1.0 to 5.0, with a mean value

of 1.76 and a coefficient of variation of 43%. In no case was the retardation factor less than 1.0.

A commonly-used equation for relating the solute retardation factor to the slope of a linear sorption isotherm is

$$R = 1 + \frac{\rho K_d}{\theta}$$

where K_d is the isotherm slope, ρ is the soil bulk density, and θ is the volumetric soil water content. Back-calculating values of K_d from the observed values of R, and assuming nominal values of 1.4 Mg m^{-3} and 0.25 for ρ and θ, respectively, the mean value of K_d is 0.14 mL g^{-1}, with a range of 0.0 to 0.9 mL g^{-1}. Thus, there was a wide range in the soil's affinity for bromacil across this small field. The laboratory-determined K_d value of 0.5 mL g^{-1} falls within the range of the field values.

The mean downward velocity of percolating water measured using the five tracer pulses exceeded the pore water velocity calculated from a plug-flow model by a factor of two to three in this experiment (see 1985 Annual Report by R. C. Rice). This indicates that a significant amount of bypass or preferential flow occurred by downward-moving water during leaching. Since the measured bromacil retardation factor was less than two, bromacil was actually moving downward at a rate faster than predicted for an unretained chemical under plug-flow conditions, wherein all the stored profile moisture participates in miscible displacement. These results provide an example of a case in which the physical process of non-uniform water flow dominated the chemical process of sorption in controlling pesticide leaching.

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PERSONNEL

R. S. Bowman, R. C. Rice, Herman Bouwer, G. C. Auer, and J. B. Miller

Table 1. Physical and chemical properties of bromacil

		Ref.
Vapor density (mg L^{-1})	$3.0*10^{-6}$	1
Aqueous solubility (mg L^{-1})	815	1
Organic Carbon Partition Coefficient (mL g^{-1})	72 (CV=102%)	1
Degradation Half life (days)	350	1
Henry's constant (K_H)	$3.7*10^{-8}$	1
Acid dissociation constant (pKa)	9.1	2

1. Jury et al., 1984
2. Weber, 1971

Table 2. Schedule of irrigations and tracer/herbicide additions

Date (1985)	Irrigation Amount (mm)	Tracer/Herbicide Name	Tracer/Herbicide Rate (g m^{-2})
22 March	125	-	-
4 April	75	2,6-DFBA	2.34
		PFBA	2.99
16 April	75	Hyvar-X	3.94
1 May	75	o-TFMBA	1.49
15 May	75	m-TFMBA	1.49
6 June	75	Br^-	12.4

Table 3. Application uniformity and recovery of PFBA from surface samples.

	Subplot 2	Subplot 4	Subplot 13	Combined
Mean (g/cm^2)	256	205	281	247
C.V. (%)	51	46	31	44
Mean Recovery (%)	86	69	94	83

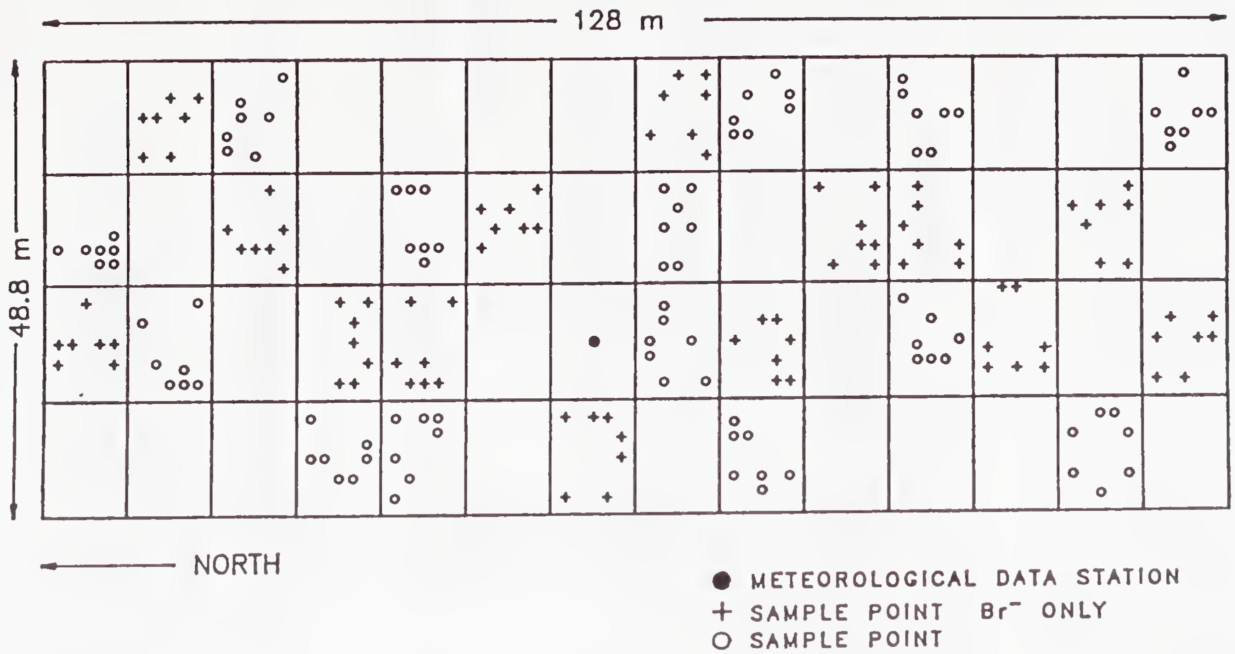

Figure 1. Diagram of field plot, showing core sampling positions. Circles represent cores taken to 2.7 m, in subplots treated with all five tracers and Hyvar-X; +'s represent cores taken to 1.8 m, in subplots treated only with Br^-.

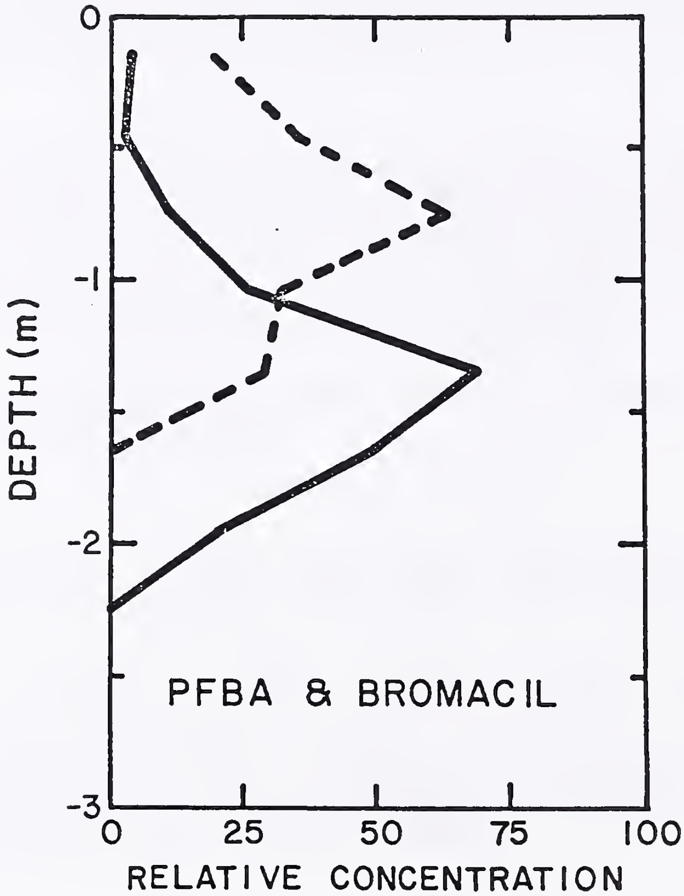

Figure 2. Bromacil (dashed line) and PFBA (solid line) distributions with depth for core sample 4-1.

TITLE: INCORPORATING SPATIALLY VARIABLE INFILTRATION INTO BORDER IRRIGATION MODELS

NRP: 20790 CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

Although numerous border irrigation models exist and can be used to calculate irrigation uniformity for a wide range of physical and managerial conditions, these models rarely take into account the effect of variable infiltration in their predictions. This study investigated the effect of spatially variable infiltration on irrigation uniformity and how to best incorporate this condition in the model simulations.

PROCEDURE

The depth of infiltration was broken down into its component parts: the opportunity time for infiltration and the infiltration potential of the soil as described by an infiltration equation and its parameters. Expressions for the mean and variance of the infiltration depth were then derived, which depend on the means, variances and covariances of the opportunity time and infiltration parameters.

For Phillip's two-term infiltration equation, expressions for the mean and variance can be written as

$$\mu_I = \mu_s \mu_x + \mu_a \mu_t$$

$$\sigma_I^2 = \mu_s^2\sigma_x^2 + \mu_x^2\sigma_s^2 + \sigma_s^2\sigma_x^2 + \mu_a^2\sigma_t^2 + \mu_t^2\sigma_a^2 + \sigma_a^2\sigma_t^2 + 2\mu_a\mu_s\sigma_{tx}^2 + 2\mu_t\mu_x\sigma_{as}^2$$

$$+ 2\mu_a\sigma_{tsx}^3 + 2\mu_t\sigma_{asx}^3 + 2\mu_s\sigma_{atx}^3 + 2\mu_x\sigma_{ats}^3 + 2\sigma_{atsx}^4$$

where I is infiltrated depth, t time, x the square root of time, and s and a are infiltration equation parameters. Estimates of infiltration variability can then be made if the distributions for the opportunity time and infiltration parameters are known.

RESULTS

In practice, the mathematical expressions for the variance of the infiltration depth can be simplified, eliminating the second line of terms. The method developed here was compared to the results of a large number of irrigation simulations. The simulations were performed using a simple border irrigation model described in 1984's Annual Report and a Monte Carlo technique. Typical border conditions and infiltration parameter distributions were used. Calculated values for the mean infiltration depth and its variance agreed well with the simulated results.

It was also found that calculated opportunity times were little affected when spatially variable infiltration rates were used during border irri-

gation simulations. Therefore, the expressions developed here can be used directly with the output from any border irrigation model to calculate the effect of variable infiltration rates on irrigation uniformity. Although this technique allows calculations of the mean and variance of the infiltration depth, care must be taken if other measures of irrigation uniformity, such as the distribution uniformity of the lowest quarter, are to be calculated, since these measures depend not only on the mean and variance of the infiltration depth but also on the type of distribution the infiltration depth follows.

CONCLUSIONS

Expressions for the mean and variance of infiltration depth were derived by a simple combination of variances technique and verified by comparing their predictions with a large number of simulated irrigations. What remains is to verify the results with field data. We are currently collecting the data required for verification of the approach.

PERSONNEL

D. B. Jaynes and A. J. Clemmens

TITLE: INFILTRATION VARIABILITY IN A FLOOD-IRRIGATED PLOT AND ITS IMPLICATIONS FOR SOLUTE MOVEMENT

NRP: 20790 CRIS WORK UNIT: 5422-20790-005

INTRODUCTION

Recently, considerable attention has been given to the effect of spatially variable soil hydraulic properties on, among other things, the fate of surface-applied fertilizers and pesticides (Biggar and Nielsen, 1976); crop yields (Bresler and Dagan, 1979); and irrigation efficiencies for border irrigation systems (Jaynes and Clemmens, 1986). Although these papers represent considerable progress in quantifying the effects of spatial variability of infiltration, much work remains to be done. Almost no information is available on the variability of infiltration during field irrigation. In this study, we describe the infiltration variability measured across a small subplot and discuss some of the implications of this variability for solute movement.

METHODS

The experimental field design and methods have been described in detail in earlier papers (Rice, Bowman, and Jaynes, 1986; Jaynes, Rice, and Bowman, 1986) and will only be summarized here. Infiltration rates were measured at 63 locations within a 12.2- X 9.15-m subplot that had been used in an earlier solute leaching experiment (Rice, Bowman, and Jaynes, 1986) covering an area of 0.62 h. We used 0.254-m diameter infiltrometers that were laid out on a 7 x 9 grid with a one meter spacing in each principle direction. Single rings were used without guard rings. Instead, the entire subplot was flooded at the same time as the infiltrometers were filled, with each receiving 0.13-m of water. Falling heads were used since this best simulates the process of flood irrigation in fields. Heads were measured within each ring with the system described by Dedrick and Clemmens (1984). Measurements were made about every two minutes.

The resulting depth vs. time data were then fit by the Kostiakov equation using non-linear least-squares regression (Jaynes, 1986) where

$$I = St^b \qquad (1)$$

and I is depth (mm), S a regression coefficient (mm s^{-b}), t is opportunity time measured from the start of infiltration (s), and b is a second regression coefficient (unitless). Equation 1 gave a good fit to all the data with an $r^2 \geqslant 0.93$ for each curve.

RESULTS AND DISCUSSION

The regression curves for the 63 infiltrometers are shown in Figure 1 for the time 0 to 15 minutes. As can be seen, there are considerable differences in the infiltration curves within this small subplot, with a

minimum infiltration depth after 15 minutes (I_{15}) of 8.5 mm and a maximum of 141.8 mm. The infiltration curves are terminated here after 15 minutes because the I_{15} values will be used later in conjunction with results from a solute leaching study (next section). The histogram of I_{15} values is shown in Figure 2a. Also shown in this figure is the normal distribution (μ = 59.1, σ^2 = 767) and log-normal distribution (μ = 3.94, σ^2 = .314) corresponding to this data. Both distributions appear to fit the data equally well with the normal curve predicting the peak of the distribution better than the log-normal curve, while the log-normal curve predicts the frequencies at the extremes better and does not predict any negative values for I_{15}, which are physically meaningless.

The histograms for the calculated S and b parameters are shown in Figures 2b and 2c. Values for each are extremely variable. The normal and log-normal curves are again superimposed on the histograms. For S, the normal distribution has μ = 1.18 and σ^2 = 0.700, while the log-normal distribution has μ = -.184 and σ^2 = 1.14. For b, the normal distribution parameters are μ = .607, σ^2 = .0132, and the log-normal parameters are μ = -.516 and σ^2 = .0345. Neither the normal nor log-normal distribution appears to fit the S data well, although the log-normal curve does predict the extreme values better. For b, the normal and log-normal curves fit the measured values equally well.

The regression coefficients are also correlated with each other, which is the same result found by Sharma, Gander, and Hunt (1980), even though they used Phillip's two-term infiltration equation instead of the Kostiakov equation. Figure 3 is a plot of ln S vs. b and shows a strong near-linear inverse correlation between the two parameters (r = -.86); that is, large values of ln S correspond to small values in b. This inverse correlation helps to decrease the dispersion in the I values for any time.

Until now, we have considered the infiltration measurements to be spatially uncorrelated. To test the spatial correlation in the infiltration data, semi-variograms were constructed for the principle axes (N-S and E-W) and the two diagonal directions. Figure 4 shows the semi-variograms for ln I_{15} for the two principle directions E-W and N-S. Each point represents a minimum of 30 pairs. Also shown in Figure 4 is the variance for all 63 measurements. Significant spatial structure is apparent in these data with correlations up to about 3-m distance. Figure 4 also shows that the spatial structure of the ln I_{15} values is anisotropic, with the ln I_{15} values being more strongly correlated in the E-W direction. Although not shown, the semi-variograms for the two diagonal directions are intermediate between these two, and thus the infiltration data exhibit a simple geometric anisotropy (p. 177, Journel and Huijbregts, 1978).

IMPACT ON SOLUTE LEACHING

We can demonstrate the implications of variable infiltration on solute movement in the field by comparing the measured results for a solute

leaching study we conducted earlier on these subplots (Rice, Bowman, and Jaynes, 1986) to the calculated results from a simple solute leaching model. In the solute leaching study, KBr was uniformly applied to the soil surface and then leached through the soil with seven flood irrigations over a 159-day period. Seven times during this period, soil samples were taken from 28 locations in the field to a depth of approximately 3 meters. The samples were sectioned into .3-m increments and analyzed for Br^-. The data were then combined to give average Br^- concentrations versus depth for each sampling period.

To simulate solute leaching under these conditions, we will use a simplified version of a model described by Parker and van Genuchten (1984) which is described in detail in Jaynes, Bowman, and Rice (1986). Basically the model consists of the standard solute transport equation

$$\partial c/\partial t = D\, \partial^2 c/\partial z^2 + \partial c/\partial z \tag{2}$$

where z is depth, c solute concentration, D the dispersion coefficient and v the pore water velocity. We assume that the first term on the right hand side of Eq. 2 is much smaller than the second term and is thus insignificant. Also, rather than use an average value for v, we assume that v follows a log-normal distribution and is related to the surface flux q, by

$$v = q/w \tag{3}$$

where w is the soil volume fraction through which flow is taking place and is assumed constant across the field. The mean and variance of ln v are therefore related to the surface flux which is proportional to the infiltration depth

$$\mu_{\ln v} = \mu_{\ln q} - \ln w \tag{4}$$

$$\sigma^2_{\ln v} = \sigma^2_{\ln q} = \sigma^2_{\ln I}$$

We can calculate $\sigma^2_{\ln v}$ directly from the ln I data; however, the mean of ln v requires an estimate of w and cannot be calculated directly from the infiltration data. We, therefore, used $\sigma^2_{\ln I}$ for the $\sigma^2_{\ln v}$ value and curve fit to find μ of ln v such that the calculated and measured concentration peaks coincided.

The variance of I at 15 minutes was used since the mean infiltration depth at this time equals the average irrigation depth during the leaching experiment. Since the calculated variance represents only an estimate of the true variance, we would like to use the calculated 95% confidence limits for the variance. However, since the I_{15} values are spatially correlated, the calculated variance is a biased (under) estimate of the true variance and true 95% limits cannot be calculated. Therefore, the values we use for the 95% confidence limits $.223 \leq \sigma^2 \leq .453$ are only approximations.

The measured time and water contents had to be transformed before we could compare the model results to the measured data since we are simu-

lating a dosed irrigation scheme by a constant flux model. The transformed coordinates were

$$t^* = \frac{\int_0^t E(q(\tau))\, d\tau}{E(q)^*}$$
$$z^* = \frac{\int_0^z 1/E(w(\zeta))\, d\zeta}{1/E(w)^*} \tag{5}$$

where $E(q(\tau))$ is the areally-averaged expected flux at time t. $E(q)^*$ is the areally- and time-averaged expected flux, $E(w(z))$ is the areally-averaged expected water content through which solute is moving at depth z, and $E(w)^*$ is the areally- and depth-averaged expected water content through which solute is moving.

The solution to Eq. 3 can be found in van Genuchten and Alves (p 32, 1982) for a slug input of tracer. The spatially averaged concentration for any time and depth is then found from

$$c(z,t) = \int_0^\infty \frac{c(z,t,v)\ \rho(v)\ \partial v}{\int_0^\infty \rho(v)\ \partial v} \tag{6}$$

where $\rho(v)$ is the log-normal distribution density function for v determined by μ and σ^2 for ln v and $c(z,t,v)$ is the analytical solution of Eq. 3 for any z, t and v.

Results for the model, using both the upper and lower estimate for the variance of ln I_{15} are shown in Figure 5 for the first six sampling dates. Also shown in Figure 5 are the 95% confidence limits for the mean Br^- concentration measured within each depth increment. The predicted dispersion in Br^- as influenced by variations in the infiltration rate accounts for virtually all the observed dispersion. Observed dispersion is slightly less than predicted for later times ($t^* > 75$ days) when Br^- has moved deeper into the soil, but is simulated closely for the earlier dates. Closer agreement at early times is not surprising since the infiltration data measure transport variability only near the soil surface. Apparently, the processes of deep percolation and redistribution are less variable than infiltration under flood irrigation.

CONCLUSIONS

One implication of this variability is that solutes will not leach uniformly through the profile over the field. Using a simple piston flow model, we showed that most of the observed spread in the average solute concentration versus depth could be attributed to variations in the depth of water applied due to variable infiltration rates. Further research is needed to test if this relationship will also hold for dif-

ferent soils and irrigation schemes. Many more studies are needed to quantify infiltration variability for a wide range of soils and conditions and identify the consequences of such variability for day-to-day soils management.

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PERSONNEL

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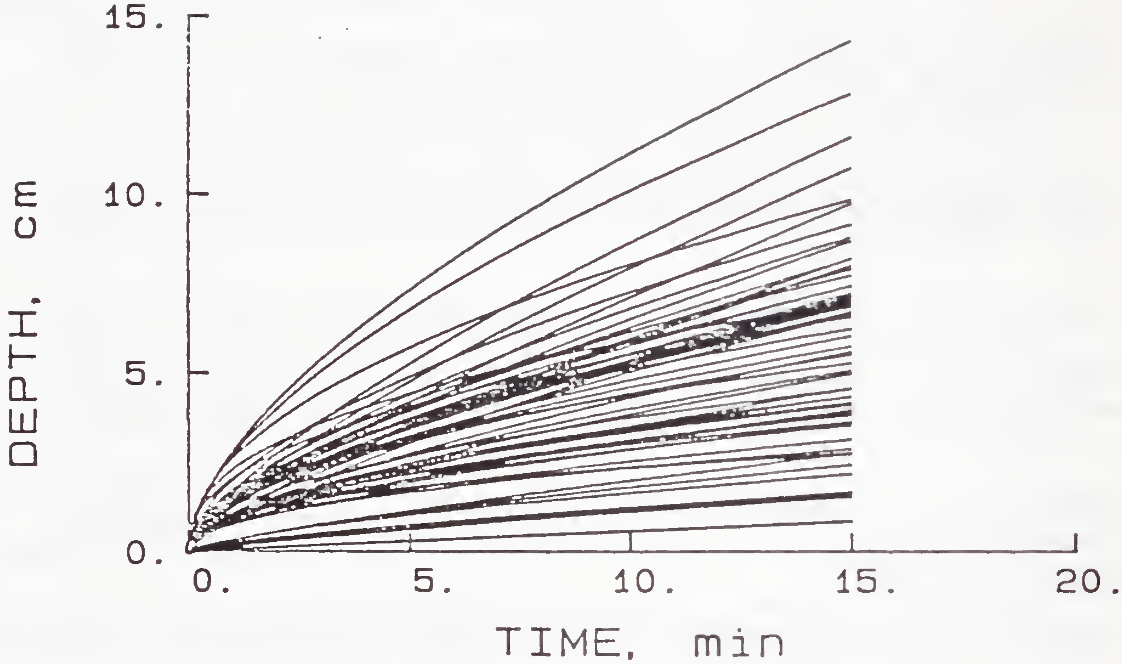

Figure 1. Infiltration curves for the 63 locations within the subplot.

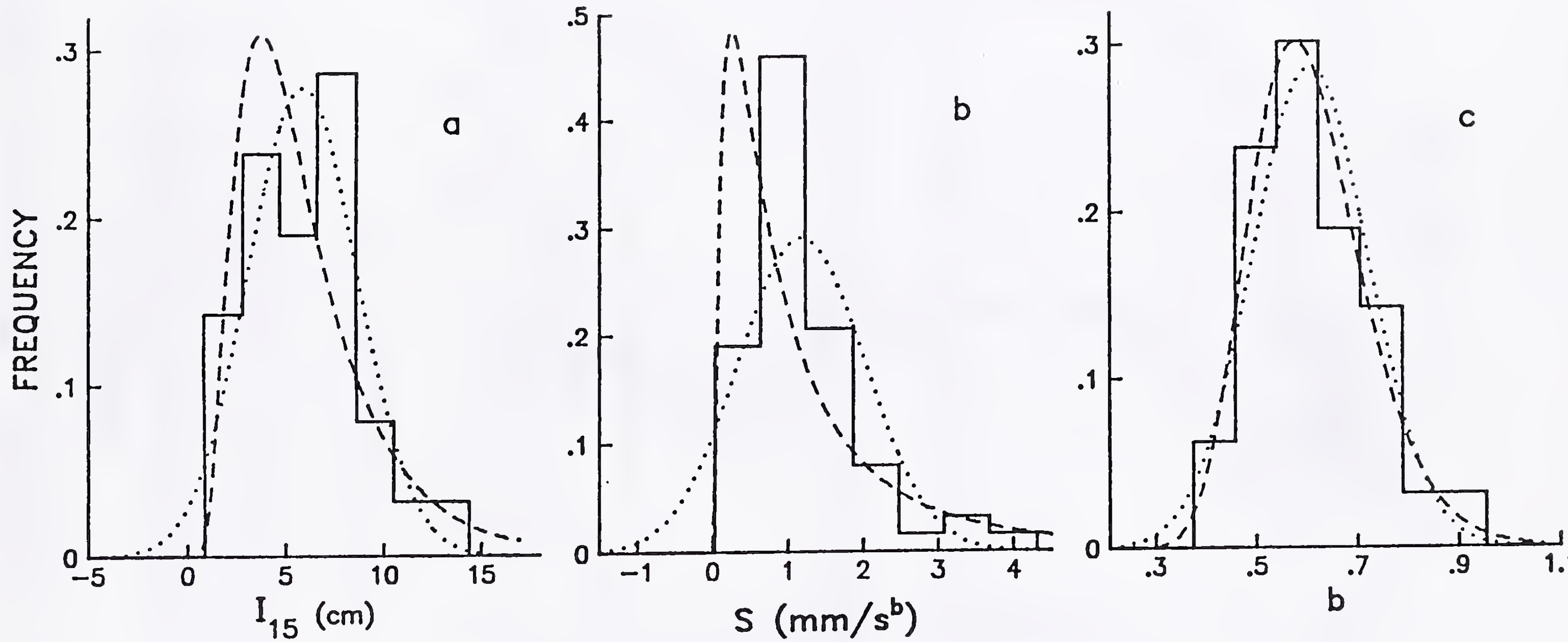

Figure 2. Histograms for the 63 infiltration curves. a) Infiltration depth after 15 minutes. b) Kostiakov S coefficient found by non-linear regression. c) Kostiakov b coefficient found by non-linear regression. Dotted and dashed curves are corresponding normal and log-normal distributions respectively.

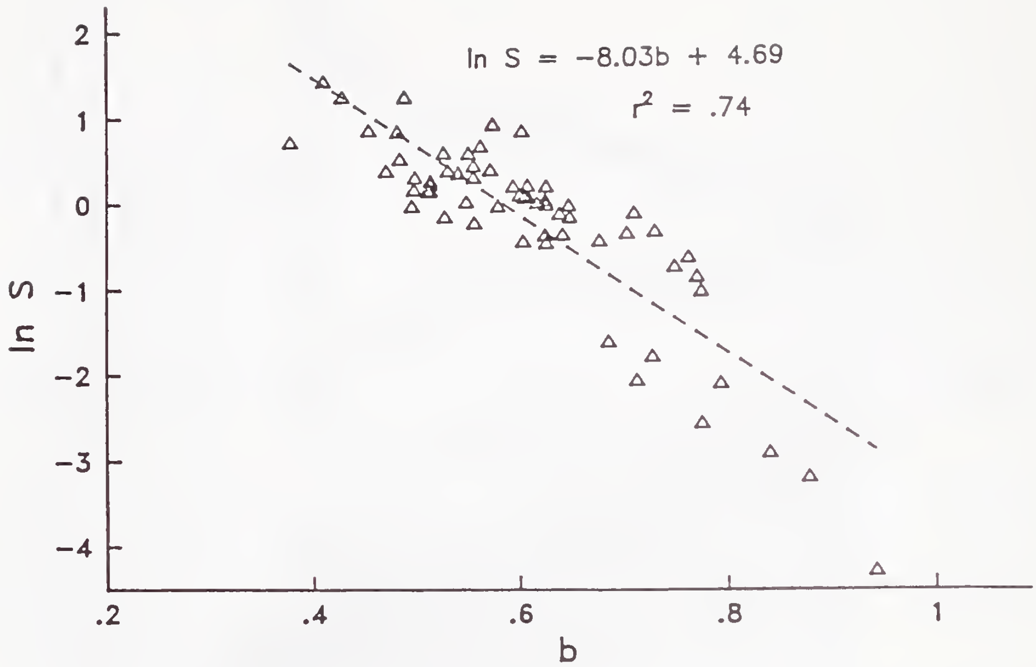

Figure 3. Plot of ln S versus b for the 63 locations. Dashed line was found by linear regression.

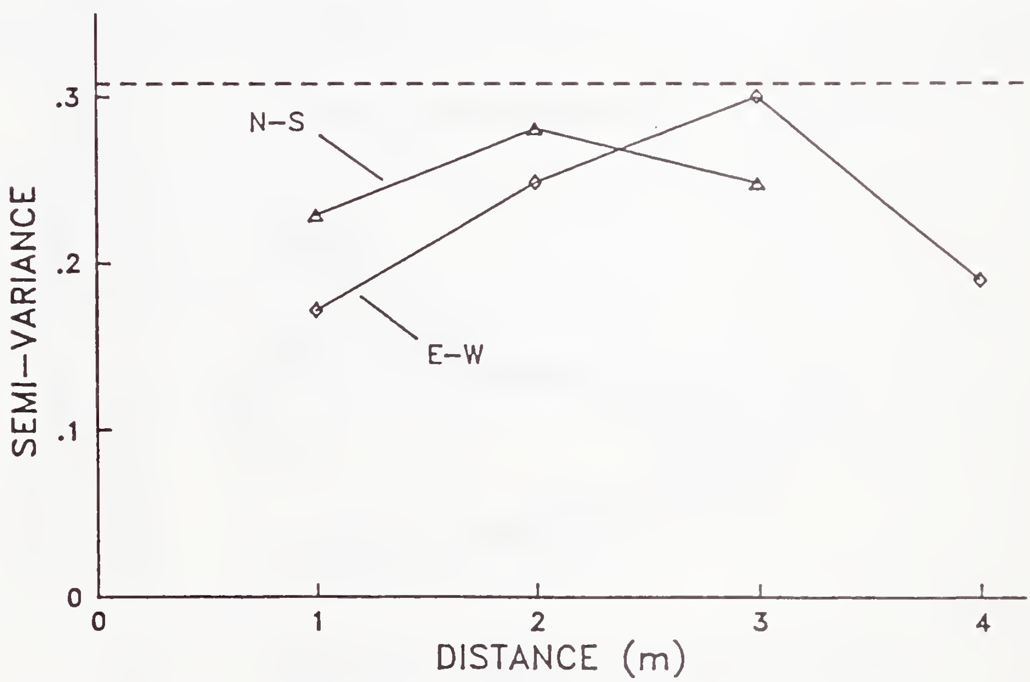

Figure 4. Semi-variogram plots of the ln I_{15} data along the principle N-S, E-W directions. Dashed line is the variance calculated for all 63 locations.

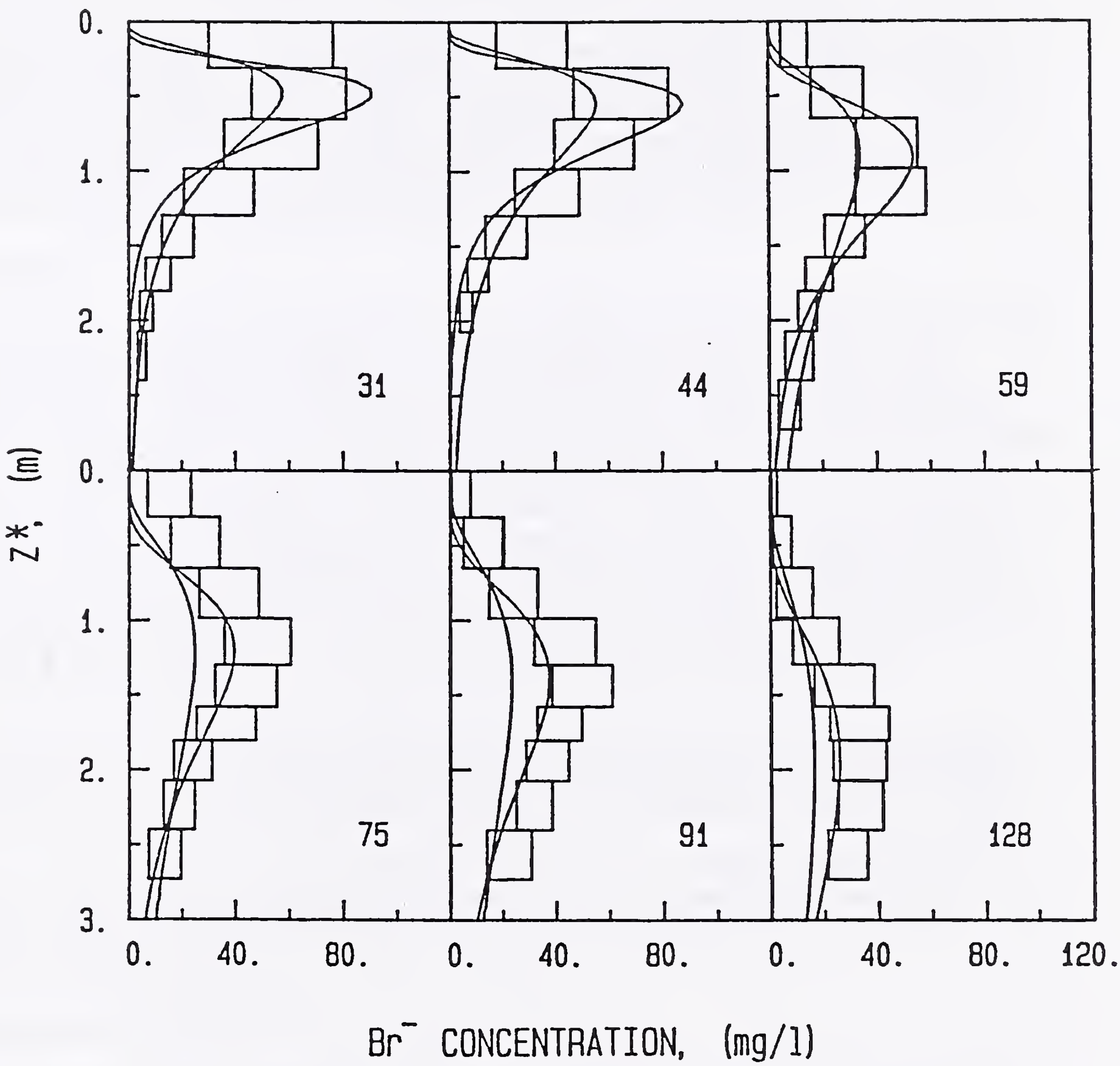

Figure 5. Measured and calculated Br^- concentrations versus depth for the first six sampling dates. The 95% confidence limits for the measured mean concentrations measured over 0.30-m increments are shown. Figure labels indicate sampling time, t^*. Smooth curves were calculated using the approximate 95% confidence values for the variance of ln I_{15}.

TITLE: LONG TERM EFFECT OF IRRIGATION ON RECHARGE AND QUALITY OF GROUNDWATER

NRP: 20790 CRIS WORK UNIT: 5422-20790-005

SPATIAL VARIABILITY OF DEEP PERCOLATION RATES

Characterization of deep percolation water as it moves to the groundwater is necessary to predict the long-term effects of irrigation on groundwater quality. The use of tracers in monitoring deep percolation rates gives point measurements. Because deep percolation may vary considerably over a field, a number of point measurements are needed to characterize the field. Determining the spatial variability is also necessary to predict deep percolation on a field basis.

PROCEDURE

Spatial variation of deep percolation rates was continued in 1985 at the Maricopa Agricultural Center. The experimental procedure and plot design are described in detail in 1985 Annual Report, "Distribution of a mobile herbicide below a flood-irrigated field." Five 7.5 cm irrigations were applied to the field at 2 week intervals. A different tracer was applied to 14 of the 56 plots before each irrigation. The last tracer (Br^-) was applied to an additional 14 plots. Seven random sites in each plot were sampled at 30 cm intervals. In the multiple tracer plots, the sites were sampled to 270 cm while the plots receiving only Br^- were sampled to 180 cm. For analysis, a 2:1 soil water extract was obtained for each sample. The multiple tracer samples were analyzed using a HPLC method. The Br^- only samples were analyzed using a Technicon procedure.

The spatial variability of evaporation was measured during one irrigation cycle. Point evaporation rates were determined at 168 locations on the field using remote sensing techniques developed by Jackson (1984).

Meteorological data was routinely collected to estimate soil evaporation. Parameters measured were solar, net, and reflected radiation, air temperature, relative humidity, soil surface temperature, soil heat flux, and wind speed.

RESULTS AND DISCUSSION

The average tracer recovery is shown in Table 1 for the different tracers and plots. Each value is the average of 7 sites. The recovery of the 2, 6DF tracer was the lowest. This was the first tracer applied, and some of the tracer moved below the 270 cm sample depth. The PFBA and the o-TFMBA tracers' recoveries were 93 and 106%, respectively. The Br^- tracer showed the highest recovery at 138%. Br^- had been applied in 1984, and residual tracer may have been in the profile. The mean recovery of Br^- from the plots that had not received Br^- previously was 130%. Another explanation for the higher recovery for Br^- and m-TFMBA is surface soil falling back into the hole during sampling. The soil surface

was dry and small amounts of soil did fall into the hole at times. The concentration of Br^- and m-TFMBA was higher near the surface than the other tracers, and consequently fall-in would increase the total recovery more than the other tracer.

A comparison was made between the Technicon and HPLC procedures for Br^- analysis. The samples from one plot were run on both systems. The results are shown in Figure 1. The concentrations from the HPLC procedure were 6% higher than the Technicon procedure. Negative interference was noted in previous studies using the Technicon procedure (see Annual Report 1984). The HPLC method would have only positive interferences, if any. The depth of peak concentration was the same for both procedures. Because the difference between procedures was small compared to the variations in total recovery, the two procedures were considered equal.

The depth of maximum tracer concentration was determined for each tracer and sample site. The values are normally distributed as shown in Figure 2 where the frequency histogram and normal distribution curve are shown for each tracer. The mean depth of maximum tracer concentration is shown as a function of water applied in Figure 3. The tracer movement was linear with water applied. The maximum, minimum, and standard variations are also shown in Figure 3.

The mean depth of maximum concentration tracer velocity and Darcy velocity for the different tracers is shown in Table 2. The velocity for the first four tracers applied varied between 1.73 and 1.85 cm/day. The average Darcy velocity was 0.42 cm/day.

The irrigation applied, evaporation and deep percolation calculated from the water balance are shown in Figure 4. The deep percolation rate was 0.16 cm/day or a factor of 2.7 less than the tracer velocity. In 1984, the ratio of tracer to water balance velocities was 5. While the value of 2.7 is less than 1984, a significant amount of bypass or preferential flow was still occurring.

The number of samples required to characterize the field was determined. Tracers were added to 14 plots in the field. Five samples were taken at 7 sites in each of the 14 plots. The mean tracer velocity and variance, using one sample per plot (14 samples) was not significantly different at the 95% confidence level from 7 samples per plot (98 samples). This would indicate that 14 samples would be adequate to characterize the deep percolation rate on this field.

The spatial variability structure within the area can be quantified by applying geostatistical methods. The relationship of each measurement to other measurements at increasing distances from that point can be determined by calculating a semivariogram defined as

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(i) - Z(i+h)]^2$$

where $\gamma(h)$ is the semivariogram and $N(h)$ is the number of pairs of observations $[Z(i), Z(i+h)]$ that are separated by a distance h, the lag. The ideal semivariogram will be zero at a lag of zero, increase until the variance is reached, and then level off. The lag at which γ becomes constant is the range. The plateau is referred to as the sill. The range represents the distance at which measurements can be considered random. In some cases, the γ will be positive value at zero lag. This is referred to as nugget effect, which may be due to variability at lags smaller than the smallest sampling distance or to measurement error.

A semivariogram for the 2,6 DFBA tracer velocity is shown in Figure 5. The range was 2.4 cm. When samples are taken at intervals greater than 2.4 m, the measurements can be considered randomly distributed. Samples spaced closer than 2.4 m are spatially correlated. Samples taken at intervals greater than 2.4 m can be analyzed using classical statistics. Spatial variability of evaporation from bare soil was also found to be correlated over space. The distance for which one measurement is spatially independent of another varied from 4.1 to 7.4 meters. The spatial structure was similar for all three stages of evaporation, indicating that the soil controls evaporation to some degree under energy limiting conditions. The variance was considerably greater during the second or transitional stage of drying than during wet or dry conditions. The mean of the point evaporation rates was the same as that calculated from one meteorological data station.

SUMMARY AND CONCLUSIONS

Spatial variability of deep percolation of excess irrigation water was measured on a 0.62 ha bare soil field. Deep percolation rates determined from the movement of tracers added to the soil before each irrigation were 2.7 times faster than calculated from a water balance. This indicates a significant amount of bypass flow or flow in preferential pathways.

The deep percolation rates and evaporation from the soil are correlated over space. The lag distance at which one measurement is spatially independent of another was 2.4 m for deep percolation and 4 to 7 m for evaporation. The mean tracer velocity and variance using 14 samples was not significantly different at the 95% confidence level from 98 samples.

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Table 1. Recovery of tracers in soil profile

Plot	2,6-DFBA	PFBA	o-TFMBA	m-TFMBA	Br^-	Br^- (only) [a/]
				%		
1	46	64	84	86	88	94
2	75	100	110	122	119	130
3	62	81	89	111	135	121
4	52	81	94	89	110	106
5	52	81	96	94	106	163
6	88	102	125	118	170	145
7	73	96	109	123	162	138
8	89	106	111	113	130	87
9	86	115	145	169	181	131
10	92	113	93	90	115	110
11	85	98	101	135	109	146
12	84	77	93	142	192	133
13	84	100	125	152	166	144
14	82	93	100	156	140	175
Average	76	93	106	121	138	130

[a/] Br^- was the only tracer applied to these plots and were analyzed using the Technicon method. All other analyses were performed with HPLC.

Table 2. Average depth of peak tracer concentration, tracer velocity, and Darcy velocity for different tracers.

Tracer	Time days	Peak depth cm	Tracer Velocity cm/day	Darcy Velocity cm/day
Br^-	6	25.1	4.16	.87
m-TFMBA	28	48.4	1.73	.39
o-TFMBA	42	77.7	1.85	.43
PFBA	57	100.7	1.77	.43
2,6-DFBA	69	126.1	1.83	.42

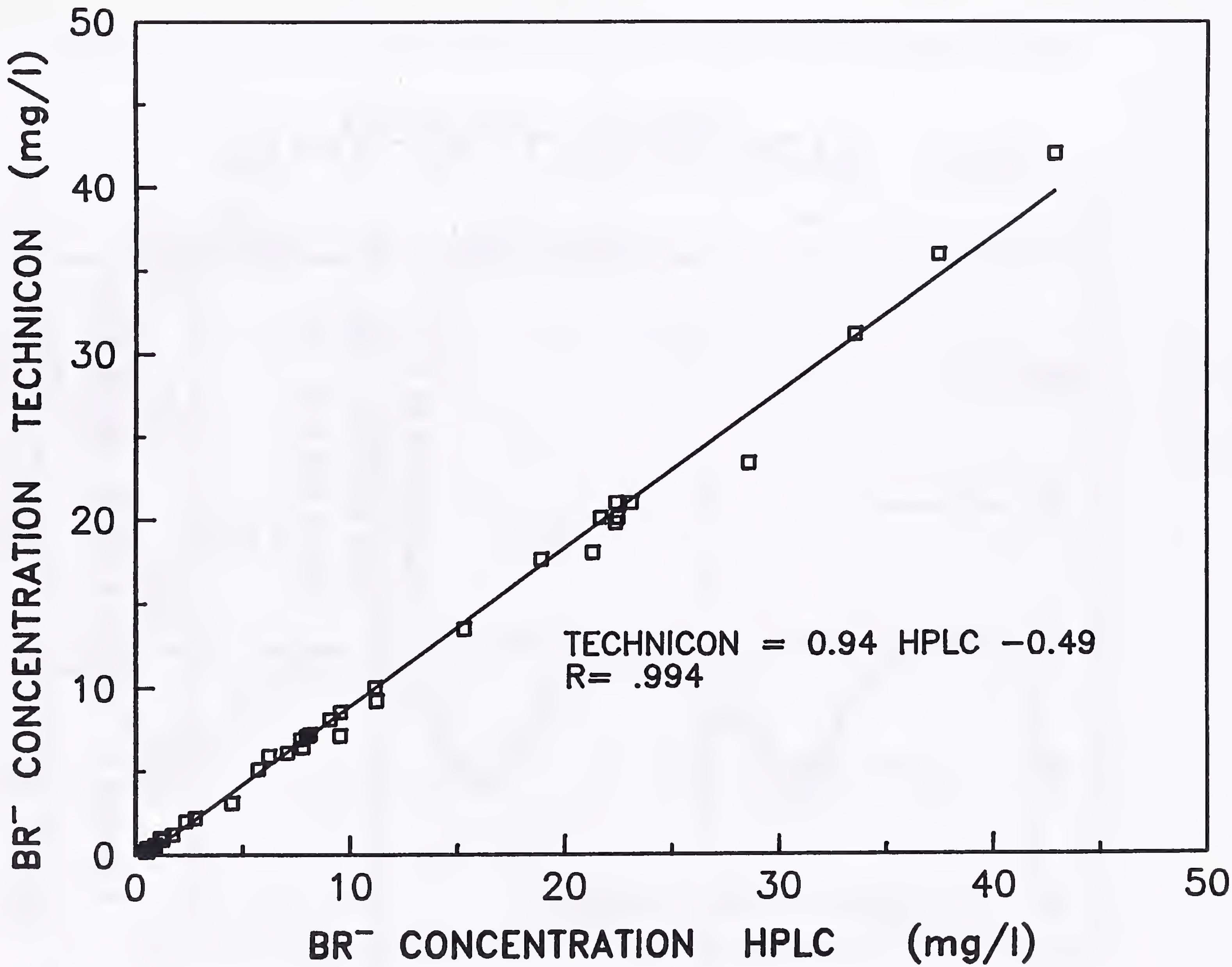

Figure 1. Comparison of Br^- analysis using HPLC and Technicon.

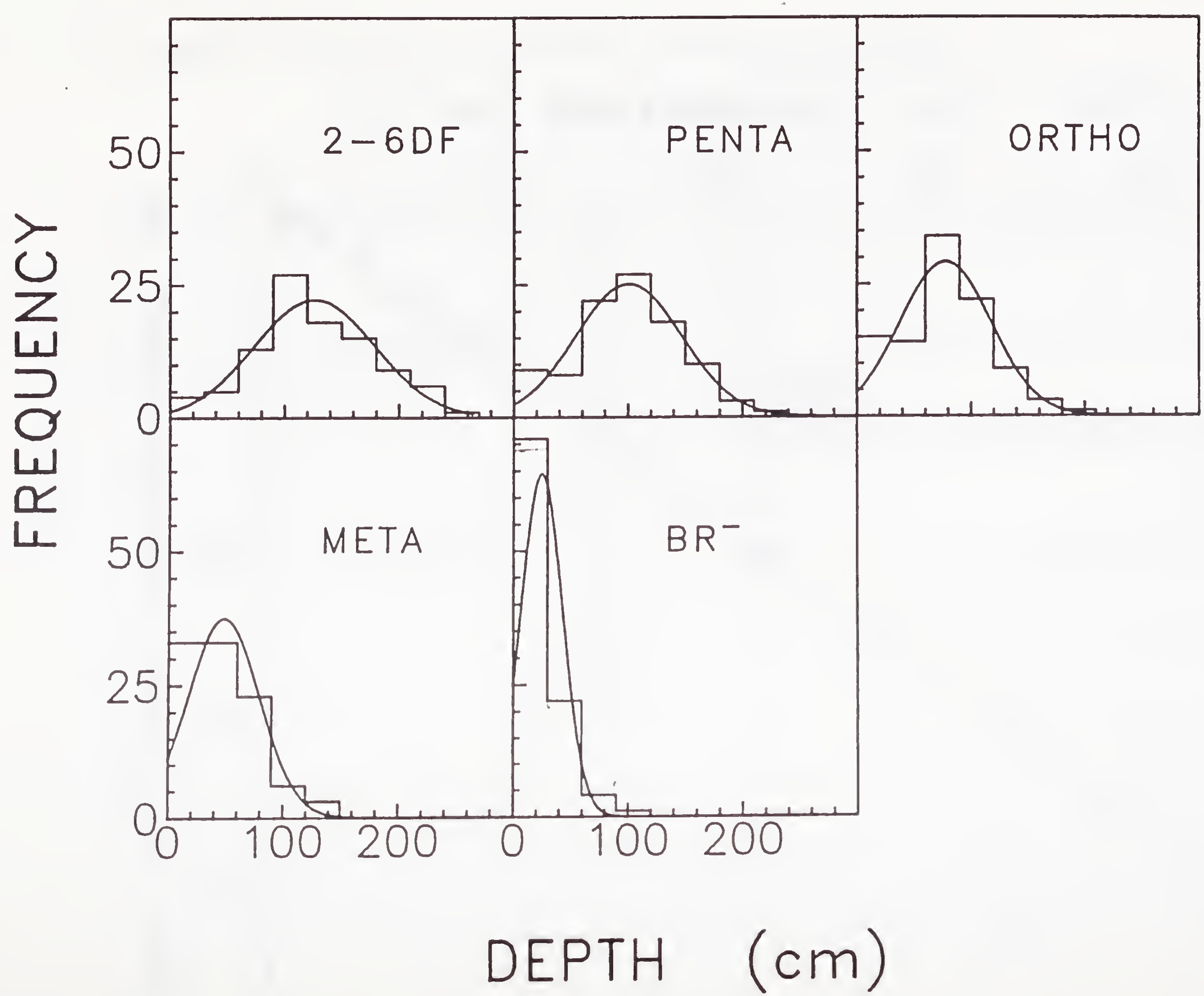

Figure 2. Histogram and normal distribution curve for the peak depth of the different tracers.

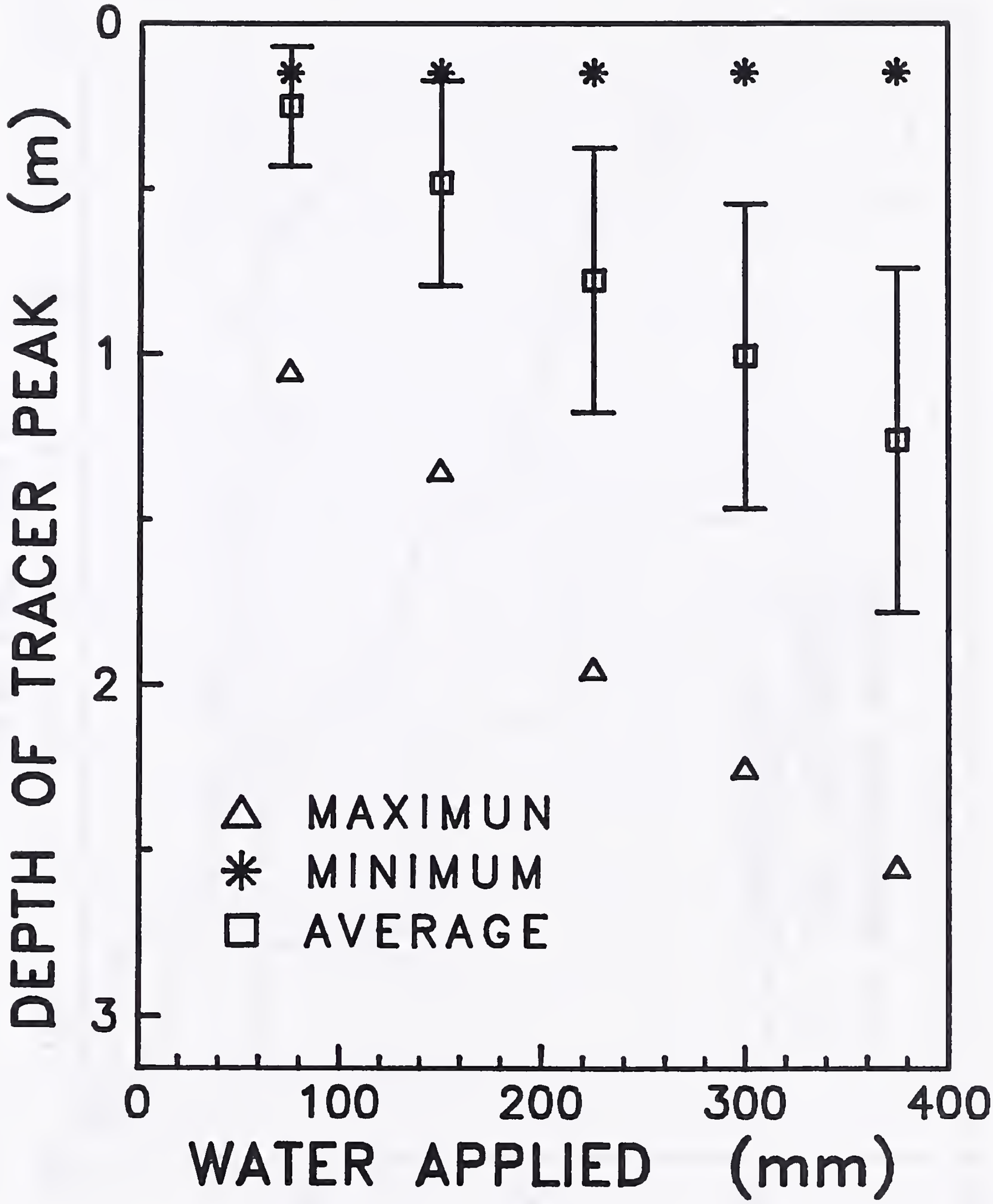

Figure 3. Depths of maximum tracer concentration for different amounts of water applied.

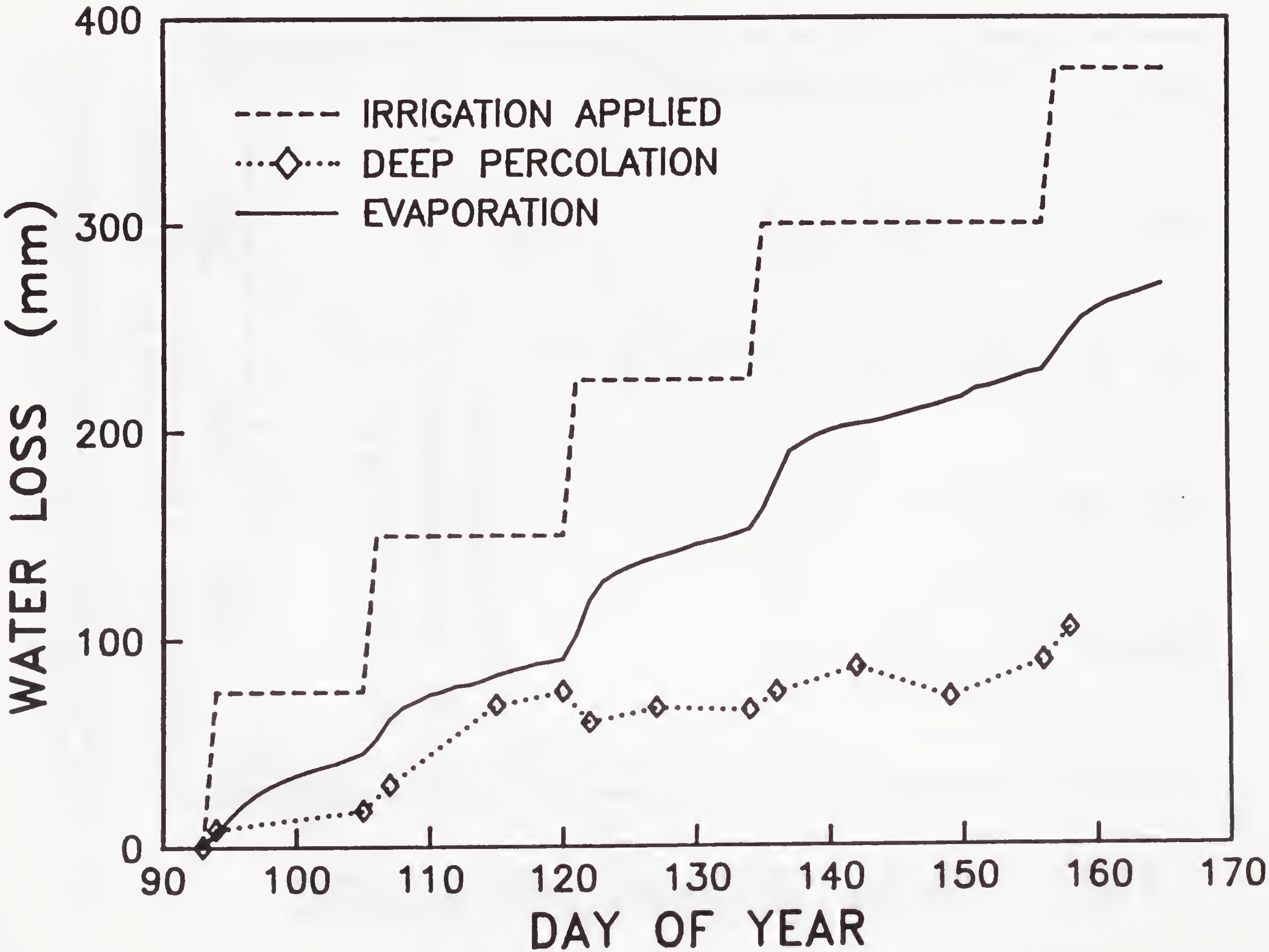

Figure 4. Irrigations applied, cumulative evaporation and deep percolation with time.

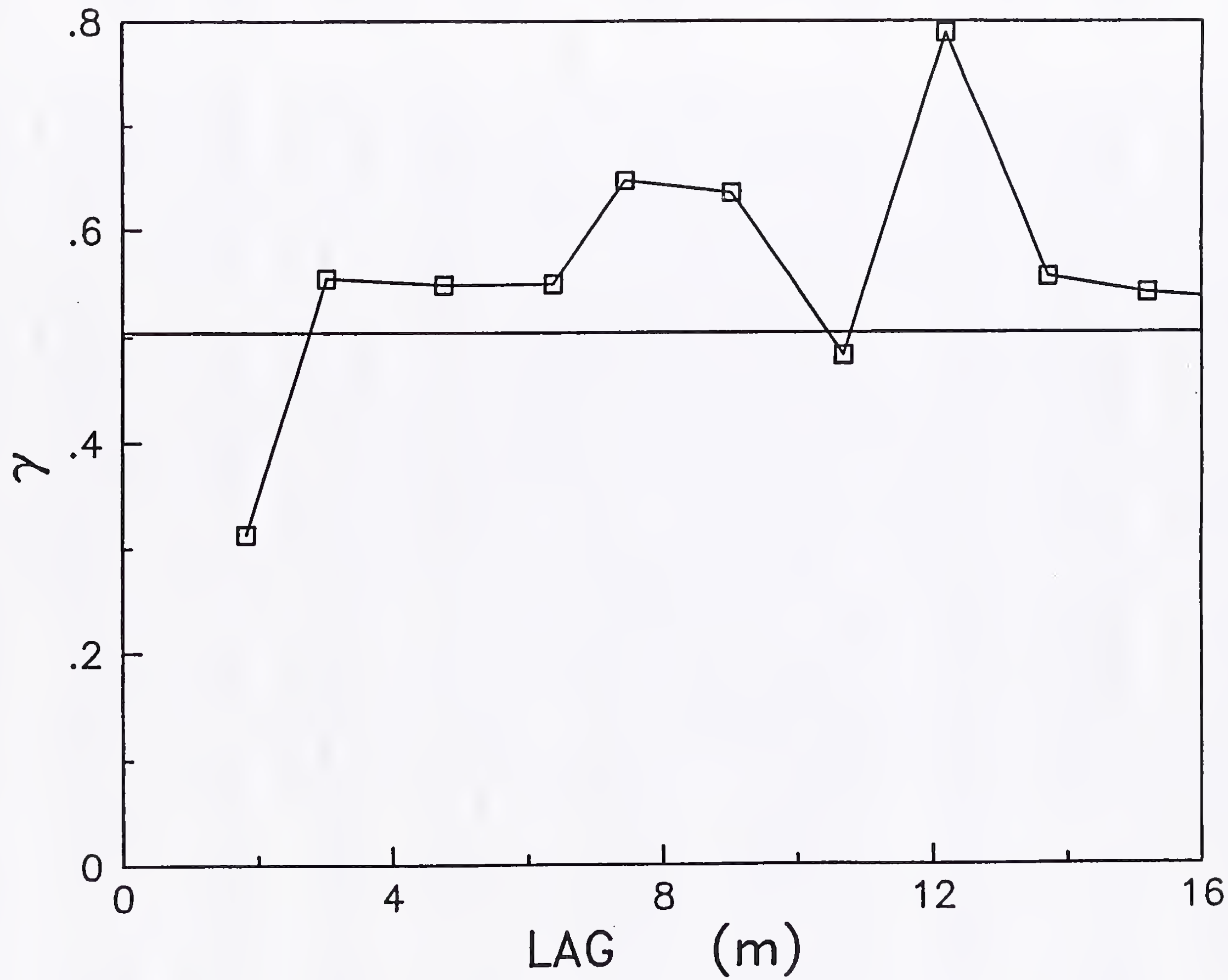

Figure 5. Semivariogram of the 2,6-DFBA tracer velocity.

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